AD No. ____

DDC FILE COPY

AD A055728

2

2

REVIEW OF MODELS OF BEAM-NOISE STATISTICS

ATLANTA • ANN ARBOR • BOSTON • CHICAGO • CLEVELAND • DENVER • HUNTSVILLE • LA JOLLA
LITTLE ROCK • LOS ANGELES • SAN FRANCISCO • SANTA BARBARA • TUCSON • WASHINGTON

78 06 [illegible] 3

6

REVIEW OF MODELS OF BEAM-NOISE STATISTICS.

14

SAI-78-696-[redacted] W/A

11

Nov[redacted] [redacted]77

12 152p.

Prepared for:

Long Range Acoustic Propagation Project
Bay St. Louis, Mississippi 39529

Prepared by:

Ocean Science Division

15

Prepared Under Contract No. NØØ014-76-C-Ø488

SCIENCE APPLICATIONS, INC.
8400 Westpark Dr., McLean, Virginia 22101
(703) 821-4300

408 414

EXECUTIVE SUMMARY

For system performance estimation and the interpretation of measured data, there is a need to predict and simulate the statistical properties of the response of a horizontally-directive acoustic array to ambient noise. In current use in the Navy there are a number of such "beam-noise" models which predict the properties of noise caused by the dominant, prevailing source at low frequencies: surface shipping. The objective of this study is to review these models in some detail and then to recommend, for specific applications, approaches which utilize the best features of each model.

Nine Navy-sponsored models were thus investigated, and all were found to be based on the fundamental hypothesis that the beam noise is the convolution of the array beam pattern with the sum of intensities from the individual ship sources. The models are then distinguishable by their treatments of the ship sources, the transmission loss (TL), and the array's response. Two categories were natural: <u>Analytic</u> models which calculate the statistical properties of noise directly from those of the components (source level, TL, etc); and <u>Brute-Force</u> models which use simulation or Monte Carlo techniques. The ability to calculate statistics over all possible values of a parameter (e.g., ship locations for a given density, all possible source levels), or over values which might occur in a short time period (say 24 hours) led to a second type of classification: "grand" and "short-term" ensembles.

The nine models have been reviewed and are described in terms of approach, treatment of ships and TL, receiver submodel, implementation, advantages, and shortcomings. Tables are given to summarize these findings.

For various applications of beam-noise models, the statistical quantities and types of ensembling required have been proposed (e.g., first-order statistics with full ensembles, or multi-array statistics), and the most promising models and techniques are identified for each. General recommendations for a LRAPP approach are:

(a) For fully-ensembled first-order statistics, use an automated version of the USI Analytic model.

(b) Use the BTL Analytic model formulas to obtain bounds on temporal statistics and to determine dominant parameters for the full ensemble.

(c) For details of fluctuations, including effects of beam patterns and TL variations, measurement interpretation, detection studies, use the best of the Brute-Force models or a synthesis.

(d) For multibeam correlation, use BTL formulas for bounds and a Bruce-Force model for details.

(e) Further investigation is required in a number of problem areas common to all of the models: Ship Information (Inputs), Wind Noise, Model Evaluation, Statistics Appropriate to Dynamic Array and Detector Simulation.

TABLE OF CONTENTS

Section 1

INTRODUCTION

This report presents a critical review of a number of the approaches currently used within the Navy for modeling the statistics of low-frequency beam noise. It concentrates on the underlying assumptions, the type and resolution of required input, and the extent of the statistics modeled. The objective is to arrive at recommended conceptual models, which utilize the best features of those reviewed, for specific applications.

"Beam noise" in this paper means the processed response (output) of a "beamed system" to ambient sea noise. A "beamed system" is an array with horizontal directivity and a beamformer which responds to plane waves in accordance with a "conventional" horizontal beam pattern (main beams and sidelobes). It is assumed that the system's temporal processing includes both narrowband filtering and incoherent averaging, so that the system output is proportional to an incoherent average of noise intensities in a narrow band. Since we focus on low acoustic frequencies, the models reviewed concentrate on the fluctuations of the surface-ship component of noise.

Nearly any of the models which predict mean beam-noise levels (TASSRAP, RANDI, FANM, etc.) can also in theory be used to predict statistics or time histories via multiple runs with inputs varied appropriately (ship densities or locations or source levels, transmission loss, beam patterns). However, this review considers only those models which are designed and structured to yield the statistical properties of noise:

A- USI Model (Underwater Systems, Inc.)
B- BTL Model (Bell Laboratories)
C- BBN Model (Bolt Beranek and Newman, Inc.)
D- WAGNER Model (Wagner Associates)
E- NABTAM Model (ORI, USI, NORDA, et al)
F- DSBN Model (Science Applications, Inc.)
G- BEAMPL (NORDA)
H- SIAM I (NRL)
I- SIAM II (NRL)

Each of these is described in Section 2, while Section 3 summarizes their attributes and makes recommendations for the synthesis of a model for LRAPP applications.

Since many of the models are without up-to-date documentation, the author (or party responsible) was asked to review a draft copy of the section of this report which dealt with his particular model. The reviewers were as follows:

Model	Reviewers
USI	R. L. Jennette Underwater Systems, Inc.
BTL	J. Goldman Bell Laboratories
BBN	M. Moll Bolt Beranek and Newman, Inc.
WAGNER	B. J. McCabe Daniel H. Wagner, Associates
NABTAM	J. J. Cornyn NORDA and E. J. Moses Operations Research, Inc.
BEAMPL/DSBN	C. W. Spofford R. G. Stieglitz Science Applications, Inc.
SIAM I	S. C. Wales Naval Research Laboratory and S. W. Marshall NORDA
SIAM II	S. C. Wales Naval Research Laboratory

Written comments were received from each reviewer, and corrections have been incorporated in the text where appropriate. The authors of this report appreciate this cooperative effort to make the model descriptions as accurate as possible.

The remainder of this introductory section describes in brief the various fluctuation mechanisms, defines beam-noise fluctuation parameters according to time scales and ensembling, and identifies the general approaches to modeling noise statistics.

1.1 FLUCTUATION MECHANISMS, TIME SCALES AND ENSEMBLES

Beam noise fluctuations are the result of any of a number of mechanisms. At low frequencies the dominant prevailing sources of ambient noise are surface shipping and wind action on the sea surface, so that the mechanisms include:

(A) surface ship movements on and off the main beams, and in the sidelobes.

(B) variations in average transmission loss (TL) from ship source to receiver caused by source/receiver (S/R) motion in a variable environment and changes in S/R separation.

(C) fluctuations in the detailed TL caused by environmental variability and, for narrow-band noise, S/R movement through the multi-path interference field,

(D) array response variation, from array distortion or signal processing artifacts,

(E) surface-ship source level fluctuations, both from changes in ship aspect and from fluctuations in the short-time averaged radiated noise itself,

(F) variations in wind-generated noise, caused by changes in the environment, wind speed and direction.

None of the models reviewed explicitly treats all of these. If we disregard time scales, system details, and ensembles for the moment, then the mechanisms believed to be most important and modeled most often are ranked in order above. The fluctuations and directionality of wind noise (F) may be very important in some circumstances, but little is known about them and the models considered do not predict them.

In order to properly compare and assess the beam noise models, we must better define the quantities to be estimated - the beam-noise statistics. Assuming that the model output is to be used to assess system detection performance and avoiding a treatise on detectors, we simply state some typical applications of beam-noise description:

- instantaneous detection probability
- cumulative detection probability in several hours or a day
- distribution of holding times or non-holding times in a day,

and some corresponding beam-noise "statistics":

- distribution of beam-noise level over a short time period (minutes to an hour)
- statistical dependence of noise at points in time separated by minutes to hours or a day,
- distribution of beam free times, over hours or a day,
- distribution of time intervals for which noise is below a threshold, over an hour or a day.

Now, each of these statistical distributions or correlation functions is based on a temporal "average" over the time period specified. For example, if beam noise was observed as a time series $N(t)$, then its distribution function over period $t_1 \leq t \leq t_2$ is simply the distribution function of the set of points $\{N(t) | t_1 \leq t \leq t_2\}$ with each point in time (t_1, t_2) equally likely ; $F_n(X) = P[N(t) \leq X$ for $t_1 \leq t \leq t_2]$. In estimating such a distribution function with a noise model, the environmental and noise-source conditions can change only as much as would be observed in that time period (say, $t_1 \leq t \leq t_2$). In most applications, the system performance is to be described for an ensemble of conditions, e.g., over all ship distributions consistent with some average densities, or over transmission loss conditions occurring in a week or throughout a geographic area. The appropriate quantities to be estimated by the noise model are then the ensemble of the time statistics discussed above, e.g., the set of distribution functions $\{F_{N_i}(X)\}_I$ generated when the ensemble of conditions is considered (denoted by an index set I). If short-term statistics are desired, then it is usually a mistake to "average" over the ensemble. Again, as an example, suppose that over given conditions i, the noise distribution function $F_{N_i}(X)$ is normal with mean μ_i and variance

σ_i^2. These are the quantities which determine detection probability. If the ensemble of conditions is indexed by a finite set $i \epsilon I$, then the ensemble distribution function $F_N(X)$ is found as

$$F_N(X) = P[N_i(t) \leq X \text{ over all } t \text{ and } i],$$

$$= \sum_{i_o=1}^{n} P[N_{i_o}(t) \leq X | i=i_o] . P(i=i_o)$$

$$= \frac{1}{N} \sum_{i_o=1}^{n} P[N_{i_o}(t) \leq X] \; ,$$

i.e., $F_N(X)$ is the <u>average</u> of the distribution functions of the F_{N_I}, is no longer normal, and may have a very large σ^2 - larger than any of the individual σ_i^2. This type of result can be very misleading in the calculation of detection probabilities.

The usual probabilistic treatment of the time-average/ensemble-average problem is to use assumptions about the ergodicity (and hence stationarity) of a noise <u>process</u> $N(t,i)$ (a time series for each $i \epsilon I$, a random variable over the ensemble $i \epsilon I$ for each fixed t). In that case, "long" time averages, over many independent samples, and ensemble averages are equivalent:

$$P[N(t,i_o)\leq X, \text{ over all } t]$$
$$= P[N(t_o,i)\leq X, \text{ over all } i].$$

There may be justification for the ergodicity assumption for noise over some specific ensembles, but in general for the problems of interest here there is no basis for it - and even if there were, the time average would be over very long periods.

To conclude we list below the typical time scales for the fluctuation mechanisms identified at the beginning of the subsection:

Mechanism	Typical Time for a Significant Change
• Ships on and off beams	Minutes for Nearby Ships, Hours to Days for Distant Ships
• Average TL variations	Hours
• Detailed TL fluctuations	Minutes to Hours
• Array response variations	Minutes to Hours
• Ship source level variations	Hours to Days
• Wind noise variations	Hours to Days

1.2 GENERAL APPROACHES TO MODELING BEAM-NOISE

As mentioned earlier, all of the models reviewed here concentrate on the ambient noise component resulting from surface-ship sources and treat wind noise only as an additive, empirical term.* Hence, those attributes which distinguish one model from another are the input requirements, the model output, the methods of calculating the noise properties, and treatments of ship sources, TL and array response.

Each model is based on the following expression for beam noise intensity:

$$N(t) = \sum_{j=1}^{J(t)} SL_j(t) \cdot T_j(t) \cdot AG_j(t), \qquad (1\text{-}1)$$

where $J(t)$ is the number of ships at time t,

$SL_j(t)$ is the source intensity of the j-th ship at time t,

$T_j(t)$ is the transmission ratio for ship j at time t (i.e. $TL = -10\log(T_j)$),

$AG_j(t)$ is the array response for the arrivals from ship j at time t.

---

*NABTAM is an exception. It calculates a directional, time-independent wind-noise component.

When all of these quantities are known, deterministic functions of time, then N(t) is directly available from (1-1); this is the way that most average-noise models work, (i.e., "point" models such as TASSRAP or RANDI).

The form of (1-1) is not meant to imply that the individual factors are necessarily uncoupled. In fact, in some of the models the source intensity and array response depend on the transmission ratio (e.g., multipath angles for a geometric treatment). In the same vein, a precise model of the temporal behavior of SL would have to reflect the transmission travel times. Finally, for some applications it might be necessary to perform the summation of intensities in (1-1) on a phased basis.

Consider now two basically different approaches to computing beam-noise statistics.

Analytic Approach: An Analytic approach is one in which the variables of (1-1) are treated as random processes with well-specified statistical properties, such as k-dimensional distribution functions. Standard probabilistic techniques (convolution, characteristic functions, etc.) are then used to calculate statistical properties of N(t) from those of SL, T, AG and J. For example, if all the

variables in the sum of (1-1) are independent, then the mean value of the noise intensity can be found directly from the mean values of the terms in the sum. Such an "analytic" approach is attractive since it can produce an efficient model for predicting selected noise statistics and for identifying the mechanisms which are important. On the other hand, the calculations can become complicated when higher-order moments or distribution functions or "short-term" statistics as described above for N(t) are required. Moreover, some of the assumptions required to make the calculations tractable may be unrealistic, and not all of the statistical properties of N may be available. It is the clever implementation of the approach which makes it useful.

The BBN, WAGNER, BTL, and USI models employ an Analytic approach.

<u>Brute-Force Approach</u>: The second approach can be viewed as a special case of the Analytic approach, in which the statistical properties of N(t) are evaluated numerically - by calculating realizations of N(t) for specific values of SL, T, AG and J. All of the quantities of (1-1) are treated as known and deterministic for a single realization of N(t) over some time period, say $0 \leq t \leq T$. In

particular, ship tracks and source levels, transmission loss versus range, angles and time, and the array response are all specified over [0,T]. This might be the case when the results of a measurement exercise are to be simulated with the model. If there is to be ensembling over any of these variables, then additional realizations of N(t) are generated from new ship tracks or TL or whatever. This is usually called a Monte Carlo simulation in that the description of N(t) over the ensemble of conditions is found. It is not (necessarily) a Monte Carlo method in the ordinary statistical sense that the individual estimates are combined and the combination converges to some ensemble descriptor (e.g., the distribution of the mean value).

The Brute-Force approach can use all of the information about ships, TL, and array response available and can yield just about any noise statistic including the "short-term" properties mentioned above. On the other hand, it can be very time-consuming, often requiring many realizations to cover the ensemble conditions and must rely on special analysis routines to summarize or process or interpret the large amount of output.

BEAMPL (NORDA), DSBN (SAI), SIAM I and II (NRL), and NABTAM (NORDA) are Brute-Force models.

In summary, each of the two approaches has advantages and disadvantages, whose importance depends on the application of the model predictions. The term "Brute-Force" is not meant to suggest that such models are unsophisticated or lack mathematical insight. Nor should the term "Analytic" convey more than the notion that the calculation is performed without direct realizations of the random variable (a numerical calculation of a characteristic function and its inversion can be as tedious as a Monte-Carlo computation).

Section 2

REVIEW OF BEAM-NOISE MODELS

This section describes each of the nine beam-noise-statistics models, concentrating on: the input requirements, treatment of ships, TL, array response, computer calculations, output quantities and analysis, status of computer codes and documentation. The order in which the models are presented and the number of pages devoted to a single approach were convenient to the author and have no other significance.

An attempt has been made to utilize consistent notation for the model descriptions:

- N or I: noise intensity
- SL: source intensity
- T: transmission ratio
- TL: transmission loss (10 log T)
- AG: array power response

R: range from array

ϕ or ψ: bearing from array or angle from array broadside*

θ: vertical angle of arrival

J or K: number of ships

λ: mean of Poisson variable

v: speed

μ: mean

σ: standard deviation

f: density function

ϕ: characteristic function*

P: probability

E: expected value

Var($\cdot$): variance

Finally, a few definitions are reviewed.

For random variables $X_1, X_2, \ldots, X_n$, the multivariate density function

$$f_{X_1, X_2, \ldots, X_n}(x_1, x_2, \ldots, x_n)$$

*There should be no confusion in using "ϕ" for the characteristic function and for bearing angle.

will be called, according to standard terminology, an n-dimensional or n-th order density function. A set of random variables $X(t)$, indexed by t, is a random process or stochastic process. Its n-dimensional density is the multivariate density of

$$X(t_1),\ X(t_2),\ \ldots,\ X(t_n)$$

for indices t_1, t_2, ..., t_n. A sample path or realization from $X(t)$ consists of a sample from $X(t)$ for each index t. An n-th order statistic for $X(t)$ is a statistic which depends (nontrivially) on the n-dimensional density. Hence, the mean, variance, skewness, median, and one-dimensional density for $X(t)$ are first-order statistics, while the autocorrelation function of $X(t)$ is a second-order statistic.

The characteristic function for a random variable X is

$$\phi(\omega) = E(\exp(i\omega X)).$$

2.1 USI MODEL

2.1.1 Background

Name: (USI Array Noise Model, Version 1) (USI)

Developer: Underwater Systems, Inc.,
R. L. Jennette and E. L. Sander

Sponsor: Applied Physics Laboratory,
Johns Hopkins University

Previous Applications: APL/JHU and LRAPP studies

Published Documentation: Reference A-5, A-6

2.1.2 General Approach

The USI model uses an Analytic approach. It numerically estimates the ensemble and time-averaged, one-dimensional statistical distribution function of beam noise using:

- Time-averaged ship densities for each of a set of contiguous geographical regions
- Poisson model for ship counts in each geographic region
- Uniform model for ship locations in a region

- Input averaged TL versus range
- Input TL fluctuation distribution
- Input ship source levels and fluctuation distributions
- Input azimuthal array beam pattern
- Incoherent addition of ship contributions

Preparation of the data and the formula (1-1) lead to a random-variable model for noise intensity (I) at the array output of the form

$$I = \sum_{k=1}^{K} [\sum_{n=1}^{J_k} I_k(n)] \qquad (A-1)$$

where $\{I_k(n)\}$ are random variables representing the possible intensity contributions from single ships. $\{J_k\}$ are Poisson variables representing the corresponding ship counts, and K is the number of distinct, per-ship, intensity distributions. The assumption is that $\{I_k(n)\}$ and $\{J_k\}$ form a set of independent variables, and that $I_k(n)$ has the same distribution for all n when k is fixed. The computer code numerically estimates the distribution function (with 1-1/2 or 3 dB resolution) from equation (A-1) using input mean values of $\{J_k\}$ and consistently precise approximations to the distribution functions of $\{I_k\}$.

A typical computer run (execution only) costs less than a dollar, and the code produces supplemental information about which ships are dominant in determining the mean and variance of the noise. Only first order statistics are available. The USI model differs from the others in its fast numerical approach to estimate the ensembled one-dimensional distribution function for beam noise.

2.1.3 Model For Ships

At present the ship fields and intensity estimates are constructed manually. The usual ship data are average ship densities for ocean regions, say $1^{o} \times 1^{o}$ cells or $5^{o} \times 5^{o}$ cells. Within each region the actual number of ships is treated as a Poisson variable, independent from one region to another (at a fixed time), and the ships are assumed to be distributed uniformly in the region.

The Poisson assumption is consistent with classical probability models for distributing points in space when the points are not allowed to cluster (see, e.g., Feller (1957), p. 149). That assumption is also critical to the formulation of the USI approach, which uses a special property of the Poisson variable: if the ship

count in an area is a Poisson variable with mean M and the area is subdivided into smaller, non-overlapping subregions, then the ship counts in the subregions are independent Poisson variables with means proportional to the subregion areas and with the sum of the means equal to M. In the USI approach, regions are broken up and regrouped according to the contribution of a ship in the region to the noise intensity. The Poisson assumption allows the model to treat the ship count for the grouped regions as a Poisson variable with the logical mean value. Note here that there is no explicit temporal variation of ship locations or properties.

Ships in a region are assigned a source-level density function, with 3 dB (or 1-1/2 dB, if desired) resolution. Construction of these functions is part of the manual preparation of the input.

The final step in preparation of the ship data is to group ships according to the distribution of intensity at the receiver output. This is accomplished by incorporating the distribution function for TL (and even array response) in the source level distribution as a function of the location of the region, both in range and azmimuth. The result then is that for a given

azimuthal sector, there is a set of intensity variables $\{I_k\}$ each with distribution derived as the sum of independent variables for source level, transmission loss, and array response, and there is a corresponding set of Poisson ship-count variable $\{J_k\}$ such that J_j represents the number of ships in the sector with intensity I_j.

2.1.4 Model for Transmission Loss

Transmission loss and fluctuation distribution are inputs to the USI model, and are in fact used only in the input preparation described above. To be precise, the transmission ratio (intensity loss) is treated as a deterministic, smooth or averaged function of range to which is added a fluctuation term. The smooth transmission is used to group the ship regions according to intensity contribution to the noise, while the fluctuation term is added as an independent variable to the appropriate ship source intensity fluctuations.

When the resolution of the source level and output intensity distribution is X dB (3 or 1-1/2), then the average values and distributions of the transmission ratio are normally estimated with similar precision.

2.1.5 Receiver Model

The receiver's spatial response is embodied in a deterministic beam response function (or beam pattern) - depending only on azimuth. Fluctuations in this function are incorporated in the source-level/transmission-loss distribution described above.

As for simulating temporal signal processing, the USI model does not generate temporal statistics of noise so that the filtering, averaging, etc. must be incorporated in the average levels and fluctuation distributions for source level and transmission. We note at this point that because of the way in which the Poisson model for ship counts is applied in the USI calculation, the final beam noise intensity distribution must be viewed as the result of ensembling over the entire population of ship distributions (for the given average density field). The corresponding time period in replication of ship locations required to realize this amount of variation is probably on the order of days or longer. The need (and ability) to model the details of short term fluctuations at the processor seems then to be diminished. The underlying assumption made in the USI approach is that "the noise

process has a long correlation time." More on this subject can be found below.

2.1.6 Details of the Calculation

Most of the previous discussion concerns the manual preparation of the input to the USI model. The actual computer routine operates on the input data:

I_k - intensity for group k, a random variable with given distribution function,

J_k - number of ships in group k, a Poisson variable,

to estimate the distribution function for the received noise intensity:

$$I = \sum_{k=1}^{K} [\sum_{n=1}^{J_k} I_k(n)] . \qquad (A-1)$$

There are several ways in which this distribution could be found, and it is USI's approach which makes the model unique. Consider then the "classical" approach as contrasted to USI's.

2.1.6.1 CLASSICAL APPROACH

Consider first the properties of I and the "classical" way of estimating its distribution function. Suppose that the Poisson variables N_k have mean λ_k. Then

$$P(J_k = m) = \frac{e^{-\lambda_k}(\lambda_k)^m}{m!}, \qquad \text{(A-2)}$$

$$E(J_k) = \text{Var}\,(J_k) = \lambda_k. \qquad \text{(A-3)}$$

Let $F_k(x)$ denote the distribution function for $I_k = I_k(n)$ and let

$$\phi_k(w) = E[\exp(iwI_k)] \qquad \text{(A-4)}$$

denote the characteristic function for I_k.

Now, the inner summand of (A-1),

$$S_k = \sum_{n=1}^{J_k} I_k, \qquad \text{(A-5)}$$

can be viewed as a fixed time point of a compound Poisson process (see any book on stochastic processes such as Papoulis or Parzen). The independence of the $I_k(n)$ and J_k allow for the immediate calculation of moments of S_k:

$$E(S_k^r) = \sum_{n=0}^{\infty} E(S_k^r | J_k = n) \cdot P(J_k = n)$$

$$= \sum_{n=0}^{\infty} E(I_k^r) \cdot n \cdot P(J_k = n)$$

$$= E(I_k^r) \cdot E(J_k). \qquad \text{(A-6)}$$

In particular,

$$E(S_k) = \lambda_k E(I_k)$$

$$E(S_k^2) = \lambda_k E(I_k^2) = Var(S_k) + [E(S_k)]^2 . \qquad \text{(A-7)}$$

Furthermore, the characteristic function for S_k is given by

$$\phi_{S_k}(w) = E[\exp(iw \sum_{k=1}^{J_k} I_k)]$$

$$= \sum_{n=0}^{\infty} E(iwI_k \cdot n) \cdot P(J_k = n)$$

$$= \sum_{n=0}^{\infty} \phi_k^n(w) (\frac{\lambda_k^n}{n!}) e^{-\lambda_k(\phi_k(w)-1)}. \qquad \text{(A-8)}$$

The independence of the $\{I_k\}$ and $\{J_k\}$ imply that of the $\{S_k\}$ so that the properties of I can be found from (A-6) and (A-8):

$$E(I^r) = \sum_{k=1}^{K} E(S_k^r) = \sum_{k=1}^{K} E(I_k^r)E(N_k) \qquad \text{(A-9)}$$

$$E(I) = \sum_{k=1}^{K} \lambda_k E(I_k) \qquad \text{(A-10)}$$

$$E(I^2) = \sum_{k=1}^{K} \lambda_k E(I_k{}^2) \qquad \text{(A-11)}$$

$$\phi(w) = E[\exp(iwI)] = \prod_{k=1}^{K} E(\exp iwS_k)$$

$$= \prod_{k=1}^{K} \phi_{S_k}(w)$$

$$= \prod_{k=1}^{K} e^{\lambda_k [\phi_k(w)-1)]} \qquad \text{(A-12)}$$

$$= \exp\left(\sum_{k=1}^{K} \lambda_k [\phi_k(w)-1] \right). \qquad \text{(A-13)}$$

Hence, all of the moments of I can be calculated directly from those of J_k and I_k, while the characteristic function of I is given as a simple function of that of I_k in (A-12) or (A-13). The density function for I is then the inverse Fourier transform of ϕ,

$$f(x) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \phi(w) e^{-iwx} dw. \qquad \text{(A-14)}$$

Formulas (A-13) and (A-14) combine to yield an algorithm to compute f. In fact, $\phi_k(w)$ could be calculated with an FFT (or, if I_k were Gaussian, in closed form), as could the inverse transform of (A-14). When great accuracy is not required and the distributions are assumed to be smooth, 32 or 64 point FFT's could be used with time of about 3×10^{-3} seconds each.

A related approach to finding the properties of I is to evaluate its moments directly from (A-9) and then to use an Edgeworth or other moment-expansion.

The developer of the USI model has found an alternative to these which is much more efficient and which readily yields information about the dominant factors affecting the noise statistics. It is outlined below.

2.1.6.2 USI Approach

The author of the USI model has described the approach as follows (details appear in Reference A-5).

The intensity variable, I, is viewed as in (1-1):

$$I = \sum_{\text{ships}} SL_i \cdot T_i \cdot AG_i \equiv \sum_{\text{ships}} W_i \;, \qquad \text{(A-15)}$$

with SL_i, T_i, and AG_i random variables. The grouping of ships in domains D_k such that a single ship in the k-th domain has "weight" given by the random variable W_k yields

$$I = \sum_{k=1}^{K} \left(\sum_{j=1}^{J_k} W_k \right) ,$$

where J_k is the number of ships in W_k and K is the number of domains. Now J_k is assumed to be a Poisson variable and the author writes

$$I = \sum_{k=1}^{K} J_k \cdot W_k \; . \qquad \text{(A-16)}$$

This intensity is then treated as "the sum of weighted Poisson variables."

To numerically estimate the distribution function for I of (A-16) the distribution functions for the W_k and for I are discretized in 3 dB (or 1.5 dB) steps and a recursive formula is used to determine the important contribution to I, from the lowest intensities, in order, to the highest. This procedure allows the convolution to be calculated by a simple recursion, and

limits execution costs to less than one dollar per computer run. The number of 3-dB distribution "bins" can be 50 or more, providing a range of noise levels of over 150 dB.

2.1.7 Output and Analysis

The output of the USI model consists of

- the distribution function for the noise intensity I, with 3 dB (or 1.5 dB) resolution.
- an analysis of how each geographical region contributes to the distribution, including the mean and variance.

The value of the latter is to help to focus on the important ships so that detailed fluctuation analysis can be performed. We note again that the distribution function represents a time and ensemble average over all ship locations consistent with the input densities and Poisson assumption.

2.1.8 Computer Implementation

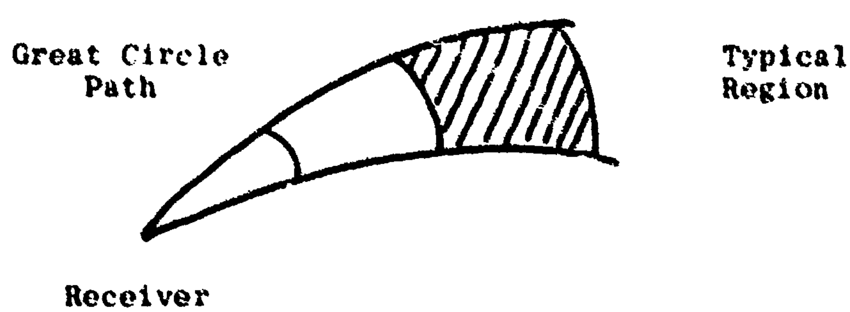
The USI program is coded in ANSI Standard FORTRAN, and is presently executed on CDC 6000-series machines and the Varian 620/L minicomputer. Core requirement is 20K, and running time is about one second or less on the CDC 6000.

2.1.9 Evaluation

Output of the USI model has been compared with the noise distribution data of Reference A-1 and showed favorable agreement, although there are questions in the interpretation of the data.

2.1.10 Significant Advantages and Disadvantages

The primary drawback for operation of the USI model is in the manual preparation of the ship/intensity groups. Ship densities must be converted to azimuthal-sector/range bins in order to group regions by intensity and beam:



USI is currently investigating the potential for utilizing FANIN, a computer routine used to prepare precisely such ship information for the FANM noise model at NORDA 320.

Other shortcomings include the fact that the USI model does not predict temporal statistics. Also, the key assumption of Poisson ship counts has not been thoroughly tested. The details of the calculation of the density function have not as yet been released, so that a critical review of the numerical routine (based on Equation (A-16)) is impossible at this time. Finally, we note that this model, and most of the analytic models, predict the statistics of noise over an ensemble corresponding to ship movements over a long time period (days). Such a prediction can be of great value for certain applications, but requires careful interpretation.

On the positive side, we note that the USI computer routine is extremely fast and inexpensive to run, orders of magnitude faster than the other models reviewed here. As a production tool, with automated ship/TL input and processing of geographic domains, the approach could be extremely valuable for a number of applications.

2.2 BTL MODEL

2.2.1 Background

Name: (BTL Noise Model) (BTL)

Developer: Bell Laboratories, Joel Goldman

Sponsor: Naval Electronic Systems Command,
Code 320 and PME-124

Previous Applications: Analysis of surveillance-system noise data

Published Documentation: References B-1, B-2.

2.2.2 General Approach

The BTL model employs an analytic approach. It was designed for the surveillance case and hence to provide a statistical description of shipping noise for a (horizontal) beamed system at frequencies in the range 25-150 Hz. The basis of this and the other noise models is equation (1-1), but the key to the BTL approach is the assumption that ships arrive randomly, according to a Poisson rule. In that case the noise intensity can be represented as a generalized shot noise process (see, e.g., Parzen (1962)), completely characterized by:

- shipping lanes*
- mean ship arrival time on each lane
- probability distribution of ship velocity and source level
- probability distribution of range/orientation of lanes relative to the beam (or equivalently, CPA range and orientation)
- the <u>deterministic</u> transmission loss,** array response, and geometry

Although the model can treat arbitrary shipping scenarios, the shot-process formulation has been exploited in special cases to yield simple analytic expressions for the statistics and an easy identification of critical factors affecting them.

Goldman has shown that the noise level distributions (in dB's) of all dimensions tend asymptotically (for large numbers of ships or for slow ships or for distant ships) to joint normal distributions. When such a situation is valid, the approach leads to an especially simple analytic model. When this is not the case, calculation of density functions is performed via Fourier inversion of characteristic functions.

*As will be discussed below, the characterization of ship traffic evolutions by lanes is necessary only to simplify calculations.

**See Reference B-3.

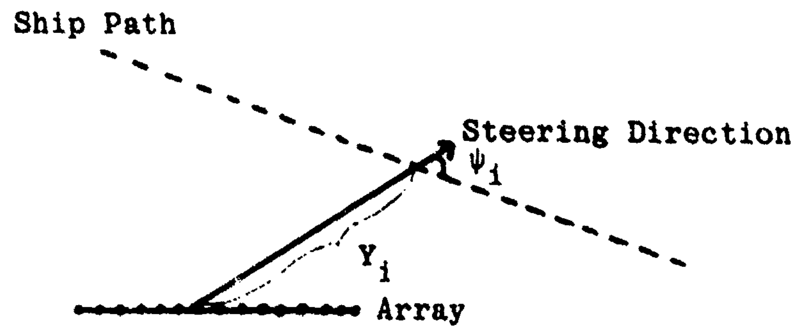
Under similar assumptions about Poisson ship arrivals, the BTL approach has been extended to the multi-beam and multi-array cases (Ref. B-2). Of special interest are the joint density functions and crosscorrelations of noise on different beams. As before, the ships drive the results (TL, SL, AG are deterministic and time-independent), analytic expressions have been obtained for special cases, and the joint densities are shown to asymptotically approach normal densities (in dB's).

The amount of input preparation and computer expense depend greatly on the particular ship scenario (e.g., number of lanes), the details of the TL, array response and source functions, and the type of output statistics desired (moments, 1-dimensional density, autocovariance, multidimensional density).

2.2.3 Model for Ships

The general formulation of the BTL model can treat an arbitrary collection of random (straight) ship paths. However, the computation is simplified by the identification of shipping lanes or "isotropic noise fields." In either case, the basis is a set of random ship paths. Each is a straight line (or, e.g., a great

circle) at a random range y_i and makes a random angle ψ_i with respect to the array steering angle.



The pairs (y_i, ψ_i) are independent and have input joint density function $f_{y,\psi}$. A single ship is assumed to travel with speed v_j and radiated intensity SL_j, both independent of time, but drawn from random populations for different ship classes. (v_j, SL_j) are independent pairs with density function $f_{v,SL}$. Finally, the number of ships, K, crossing the steering direction in a unit time interval is assumed to be a Poisson variable with mean λ (ships/hour):

$$P\{K = k\} = e^{-\lambda} \frac{\lambda^k}{k!}, \quad k = 0,1,2,\ldots \qquad \text{(B-1)}$$

This is the key to the shot-noise process. The author of the model describes an alternative for defining shipping paths in terms of bearing and range to CPA.

The model computations are simplified as the shipping paths become more structured. A shipping <u>lane</u> is made up of parallel ship paths - so that

$$f_{y,\psi}(y,\psi) = f_y(y) \cdot \delta(\psi-\psi_o). \qquad \text{(B-2)}$$

or, alternatively, a lane may be defined according to constant CPA bearings, with random CPA ranges. The author also defines an "isotropic noise field" as consisting of many paths with CPA bearing uniform in $[0, 2\pi]$, and random CPA range. Finally a ship scenario might consist of several independent lanes plus, perhaps, an independent isotropic field.

In summary, the shipping field must be composed of "straight" paths on which ships arrive according to the Poisson-rule equation (B-1). The grouping of paths into <u>lanes</u> or <u>isotropic</u> fields makes the computations easier. A ship's speed and course and source levels do not change with time, but are chosen randomly for each path from prespecified probability distributions. The

source intensity does not depend on either azimuthal or vertical angle. All of the ship field input must be constructed manually.

2.2.4 Model for TL

Transmission loss is an input to the BTL model, and is prescribed as a function of range and azimuth. It is treated as deterministic and there is no mechanism to produce random fluctuations of the TL.* The more the detail of the TL, the more complicated is the calculation of the statistics of noise. The model treats neither source coupling nor receiver response in terms of multipath or multimode transmission.* In order to derive closed-form results for special cases, Goldman has assumed an A + BlogR rule for TL.

2.2.5 Receiver Model

Energy from each noise source is assumed to arrive from the source direction in the horizontal plane as a perfectly coherent plane wave. Hence, the array beamformer is modeled with the usual array-response

*Again, see Reference B-3.

function (beam pattern); it is a completely deterministic input. The array itself is assumed to be located at a fixed geographic position and depth.

2.2.6 Details of the Calculations

For each ship contributor, the noise power at the array is given in general by

$$N_i(t) = h(t-t_i;\ v_i,\ SL_i,\ y_i,\ \psi_i) \qquad \text{(B-3)}$$

where h is simply

$$SL_i(t) \cdot T_i(t) \cdot AG_i(t),$$

t_i is the random time of arrival of the i-th ship at the beam axis. Also,

$$T_i(t) = T(R_i(t),\ \theta_i(t)),$$

$$AG_i(t) = AG(\theta_i(t)),$$

where $R_i(t)$ is the range to the source, and $\theta_i(t)$ is the source bearing (relative to array broadside), both functions of $\{v_i(t-t_i), \psi_i, y_i\}$.

Then the total noise intensity at time t is of form

$$N(t) = \sum_i N_i(t) = \sum_i h(t-t_i;\ v_i,\ SL_i,\ y_i,\ \psi_i). \quad \text{(B-4)}$$

This is a "generalized shot-noise process" (Reference A-3), completely characterized by the ship arrival density (λ_i), the function h, and the distribution functions for y_i, ψ_i, v_i, and SL_i.

Goldman shows that the ship scenario can be equivalently represented as a large collection of random ship paths (with a single λ) or in terms of several shipping lanes plus an isotropic field. He then derives formulas for the moments, correlation functions, and characteristic functions for N(t) of arbitrary dimension (in time). For example, the m-dimensional characteristic function is given by

$$\phi_{N(t_1),N(t_2),\ldots,N(t_m)}(U_1, U_2, \ldots, U_m)$$

$$= \exp\left\{\lambda \int_{-\infty}^{\infty} E\left\{\exp\left[j \sum_{n=1}^{m} U_n \cdot h(x+t_n-t_1;\ v,\ SL,\ y,\ \psi)\right]-1\right\}dx\right\} \tag{B-5}$$

where $E(\cdot)$ denotes expected value and $j = \sqrt{-1}$.

Equations of similar complexity are obtained for the cumulants, moments, etc. However, for special cases, simplified formulas are obtained. For example, if there is one ship path only, with constant values of v, SL, y, ψ, then for $h(t) = h(t-t_i;\ v,\ SL,\ y,\ \psi)$,

$$E(N) = \lambda \int_{-\infty}^{\infty} h(t)dt,$$

$$\text{Covariance } (N)(\tau) = \lambda \int_{-\infty}^{\infty} h(t)h(t+\tau)dt$$

The author devotes considerable attention to the case in which the skewness

$$C_s = \frac{E(N-\mu)^3}{\sigma^3}$$

is small. He shows in Reference (B-2) that:

> for a sequence of shot-noise processes $\left\{N_i\right\}$, if $C_s \rightarrow 0$ and the correlation $\rho_i(\tau)$ converges to $\rho(\tau)$ as $i \rightarrow \infty$, then the joint density function for N_i converges to a joint log-normal density, completely characterized by the mean, variance and correlation function.

The validity of such a proposition yields a very simple model for noise fluctuations. The condition $C_s \rightarrow 0$ is shown to hold for a lane whenever one of the following occurs:

- $\lambda \rightarrow \infty$
- $v \rightarrow 0$
- $R \rightarrow \infty$

Goldman also develops (Ref. B-2) general formulas for the joint characteristic function for two beams of one array and for two beams of two arrays.

2.2.7 Output and Analysis

The model output consists of probability density functions (of arbitrary order), with corresponding

moments and correlation functions. For special cases these have been derived in closed form; otherwise numerical integration or Fourier inversion of characteristic functions is required. The model is not set up to produce sample paths (time series samples) of the noise process.

2.2.8 Computer Implementation

Computer routines are used at BTL to perform the Fourier inversions (FFT), numerical integration, etc. The "model" is not a general production computer algorithm, so that each case and type of output must be considered.

The time and core requirements depend on the statistics and accuracy desired. For the UNIVAC 1108 computer, the following are typical:

- calculation of moments: 10K core and 5 seconds, per lane

- calculation of one-dimensional density function: 60K core and 5 minutes, per lane

- calculation of two-dimensional density function: 90K core and 12 minutes, per lane

2.2.9 Evaluation

Output of the BTL model has been compared with surveillance-array noise data and the agreement has been termed "excellent" in Reference B-2. In particular, the predicted one-dimensional density functions were compared with those measured over a nine-day period for two steering angles. The distribution functions were within 0.5 dB over the range 0.02 to 0.97, after a shift in median of 3 dB.

The ship arrival assumption was also tested against extrapolated observations of traffic. The Poisson model was accepted at a high significance level.

2.2.10 Significant Advantages and Disadvantages

The principal contribution that the BTL work can make to area assessment or system performance analysis seems to be the analytic formulas derived for special "limiting" cases. These can be used not only to predict the important beam noise fluctuation properties, but also to determine the environmental and shipping parameters which influence them. As examples of the many results derived in Reference B-2, consider

- Noise power autocorrelation depends on "average time for a ship to cross the beam" but not on ship density (λ), width of the shipping lane, or orientation of paths.

- As the skewness of the one-dimensional distribution tends to zero, the noise process approaches a log-normal process, depending only on μ, σ and the correlation function. The author shows that the condition is satisfied when there are many ships or slow ships or distant ships. The result is extended to the multi-beam, multi-array case.

- Although the overall ship scenario is very important, treatment of ship speeds or ranges as random variables (instead of as deterministic) is not usually necessary.

Even though these results do not take into account TL fluctuation or the details of the array response, they are indicative of the power of the approach.

Of all the Analytic models treated, the BTL model is the most general in the sense that it provides formulas for density functions of all dimensions and hence a complete description of the level-crossing properties and other higher order statistics of the noise.

It can also treat nearly any shipping scenario - subject only to the Poisson arrival assumption. On the latter point, Goldman has examined measured ship-arrival data and found the hypothesis to be acceptable at a high significance level.

Among the important shortcomings of the BTL model:

- Except for simplified cases, the calculation of characteristic functions, distribution functions, correlation functions, etc. is time-consuming - especially for the higher order statistics.
- The preparation of shipping lane inputs is difficult. This is of course a problem for any of the models which use more than ship densities.
- The asymptotic limit of the noise process as log-normal is an extremely powerful result. However, it is not clear that it is valid in interesting cases and requires further study.
- The key assumption about Poisson ship arrivals needs further study, both in the sensitivity of the analytic results to it and in its validity as a property of shipping traffic behavior.

In addition to these is the ensembling problem discussed in Section 1. The density functions produced by the model are derived from the ensemble over all ship locations. Since the shot process is (in most cases) ergodic, the ensemble statistics are the same as time-average statistics, over time periods very long compared to the decorrelation time. Hence, the density function for a 12 or 24 hour time period will usually not be represented by the BTL model prediction of the one-dimensional density. This is not to say that the model is incapable of predicting the properties of short sample paths; the BTL formulation can in theory provide such data, but the calculations are expected to be very tedious.

2.3 BBN MODEL

2.3.1 Background

Name: (BBN Noise Model) (BBN)

Developer: Bolt, Beranek and Newman, Inc.,
John I. Mahler, Francis J. M. Sullivan,
Magnus Moll

Sponsor: Office of Naval Research, Code 431;
Naval Electronics Systems Command,
Code 320

Previous Application:

Published Documentation: References C-1, C-2.

2.3.2 General Approach

The BBN model uses an Analytic approach, based on Equation (1-1). It involves the direct calculation of one- and two-dimensional (in time) probability density functions by inverse Fourier transform of the characteristic functions. The key to the approach is the construction of the characteristic function when ship traffic and source levels are modeled as random variables. General shipping scenarios are treated and a special model for radiated noise encompassing the discrete and continuous parts of the spectrum is used (Ref. C-3).

In the current version of the model only first-order statistics are computed. The computer implementation of the method for second-order densities has not been completed. Furthermore, only "main beam" noise, i.e., noise from a fixed azimuthal sector, is provided at present. Transmission loss and array response are deterministic inputs to the routine.

The BBN model is similar to the BTL model in that both calculate density functions directly from characteristic functions. The primary difference is that BTL assumes that the ships travel according to a Poisson rule (which in turn simplifies the calculation of the characteristic function) while BBN allows a general ship scenario.*

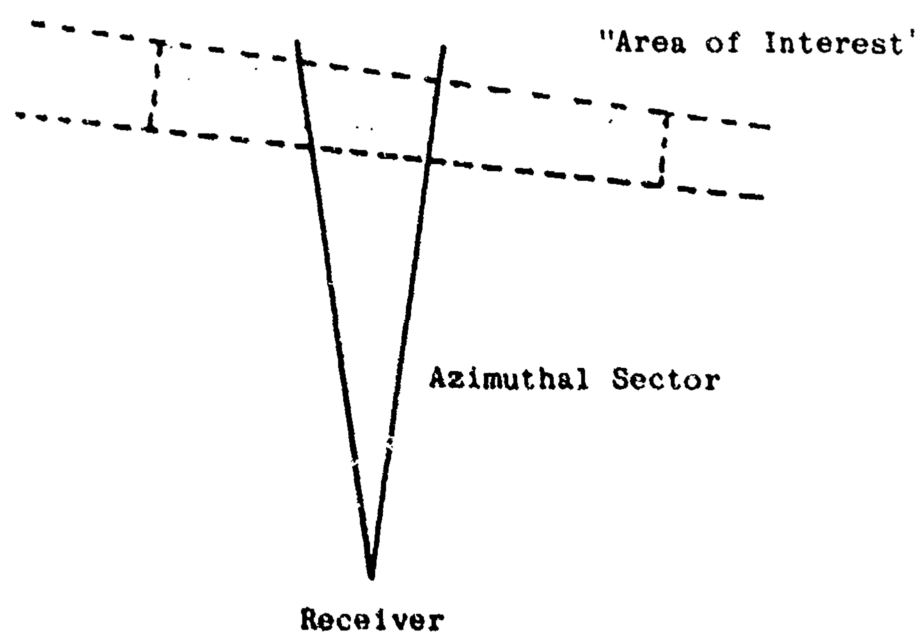
The time for the computer calculation of the characteristic function and Fourier inversion for the one-dimensional density (with 50-60 dB dynamic range) is about one CDC-6400 minute ($10). Two-dimensional densities are expected to utilize much more computer time.

---

*The version of the BBN model most recently implemented is described in Reference C-2. It is assumed there that the number of ships in the "area of interest" is a Poisson variable, as in the USI model.

2.3.3 Model for Ships

Ships are confined to a bounded domain, the basin, as in the two models described above. Merchant ship traffic is assumed to travel within "route envelopes" or "lanes." For the basic time interval of interest, say $0 \leq t \leq T$, the model need account only for the ships which pass through the azimuthal sector under consideration (the beam). Hence, for each lane the "Area of Interest" in which ships are defined looks like:



so that it contains ships which could reach the beam within $0 \leq t \leq T$.

A shipping scenario is made up of (a) individual ships of (b) several types or classes, traveling on (c) tracks within (d) routes or lanes.

Routes: The scenario consists of M routes.

Tracks: A route is made up of straight-line tracks. Track bearings are inputs. All tracks within a route are equispaced in range when viewed along the center of the array's main beam. The number of tracks within a route (track density) is chosen so that the resulting resolution is appropriate to the noise problem under study.

Types: Each ship is assumed to belong to one of N types or classes. Then, for the i-th route there is a random variable, J_{ij}, which determines the number of ships of the j-th type in the area of interest.* There is also a constant, deterministic speed, v_j, and a source-intensity random variable, SL_j (based on Ref. C-3); these are the same for all ships of type j.

*The version of the model described in Reference C-2 assumes that J_{ij} is a Poisson variable. The assumption is based on a simple model of traffic which leads to a binomial distribution, which in turn is approximated by the Poisson distribution for small segments of the route associated with small azimuth sectors.

<u>Individual Ships</u>: Initial ship positions within the region of interest are determined from the random variables:

G_{ijk} = coordinate in the direction of travel for the k-th ship of type j on route i

Q_{ijk} = coordinate normal to the direction of travel for the k-th ship, etc.

These variables determine positions on a track and across the tracks for a route. They are independent from ship to ship, but are identically distributed as a function of k. The density functions for G and Q are inputs to the model. The number of ships on a route and of a type is J_{ij}, mentioned above.

Notice that Q is the location at time of CPA and G is a multiple of the ship velocity. Since ships travel at constant speed (v_j for type j), the positional coordinates at time t are

$$Q(t) = Q.$$

$$G(t) = G + v_j \cdot t$$

2.3.4 Model for TL

Transmission loss is an input to the BBN model. It is a deterministic function of range appropriate to the azimuthal sector under consideration. The source and receiver models do not depend on vertical transmission or vertical arrival angle.

2.3.5 Receiver Model

Energy from each noise source is assumed to arrive from the source direction in the horizontal plane as a perfectly coherent plane wave. The "array response" is for an ideal beam: unit response over the prescribed azimuthal sector and zero response elsewhere. Energy from different sources is added on a random phase basis.

2.3.6 Details of the Calculation

Begin with equation (1-1):

$$N(t) = \sum_{j=1}^{J(t)} SL_j(t) \cdot T_j(t) \cdot AG_j(t). \qquad (1\text{-}1)$$

For the ships in the sector of interest, $AG \equiv 1$. The sum can be written in terms of routes, types, and individual ships after we define:

- SL_{ijk} = source intensity of the k-th ship of the j-th type on route i, a random variable, constant in time.

- (G_{ijk}, Q_{ijk}) = the coordinates at time t=0 of the k-th ship, random variables constant in time as described in 2.3.3.

- $T(G, Q)$ = the transmission ratio (intensity loss) for a source at coordinates (G, Q). It is a deterministic, time-independent variable.

- M = number of routes

- N = number of ship types

- J_{ij} = number of ships of type j in the area of interest for the i-th route.

Then (1-1) at time t=0 becomes

$$N(0) = \sum_{i=1}^{M} \sum_{j=1}^{N} \sum_{k=1}^{J_{ij}} SL_{ijk} \cdot T(G_{ijk}, Q_{ijk}). \quad \text{(C-1)}$$

Since ships of the same type travel at constant speed, v_j the noise intensity at time t is given by

$$N(t) = \sum_{i=1}^{M} \sum_{j=1}^{N} \sum_{k=1}^{J_{ij}} SL_{ijk} \cdot T(G_{ijk}+v_j t, Q_{ijk}) \quad \text{(C-2)}$$

These two equations (C-1, C-2) are the basis for the BBN approach. Notice that the random variable $N(t)$ is a function of the random variables SL, G, Q, and J, and of the deterministic variables v, t, M and N. Hence, the density functions and statistics of N are derived from ensembling of SL, G, Q, and J.

Ref. (C-1) mentions that the calculation of such densities can be performed directly with convolutions. This might proceed as follows for the one-dimensional density:

- For each i, j and t fixed, calculate

  $$P\left\{T(G_{ijk} + v_j t,\ Q_{ijk}) \leq C\right\}$$

  $$P(SL_{ijk} \leq D)$$

  $$P(J_{ij} \leq E) \qquad \text{(C-3)}$$

  These are independent of k.

- For a single ship of type j on the i-th route, find

  $$P\left\{SL_{ijk} \cdot T(\cdots) \leq C\right\}$$

  which is again independent of k. If SL and T are in dB's, then this is a convolution.

- Given (C-3) and (C-4), for a single (i,j), compute

$$P\left\{\sum_{k=1}^{J_{ij}} SL_{ijk}\cdot T(\cdots) \le C\right\}$$

$$= \sum_{L=1}^{\infty} P\left\{\sum_{k=1}^{L} SL_{ijk}\cdot T(\cdots) \le C\right\} \cdot P\left\{J_{ij} = L\right\}, \quad \text{(C-5)}$$

  which again involves multiple convolutions for the first term.

- Finally, $N(t)$ is simply a double sum of the variables given in (C-5) - so that $M\cdot N$ additional convolutions yield the answer.

Calculation of the joint density for $(N(t_1), N(t_2))$ is similar, but involves the joint distribution of form

$$P\left\{T(G+vt_1, Q) \le C, \ T(G+vt_2, Q) \le D\right\}.$$

For implementation on a digital computer, the use of characteristic functions and Fourier transforms is often a better approach than that described above. The present BBN model does indeed employ such a method. Reference (C-1) derives the formula for the characteristic function corresponding to the joint density of $(N(0), N(t))$:

$$\Phi(\alpha,\beta) = \prod_{i=1}^{M} \prod_{j=1}^{N} \sum_{L=1}^{\infty} P(J_{ij}=L) \left[\int_{\infty}^{\infty} g_{ij}(w)\cdot\Phi_{s_j}(w)dw\right]^L$$

(C-6)

where

Φ_{s_j} is the characteristic function for SL_j,

and

g_{ij} is the density function (for all k) of the variable

$$\alpha T(G_{ijk}, Q_{ijk}) + \beta T(G_{ijk} + w_j t, Q_{ijk}).$$

The latter density is found from its characteristic functions.

Since $\Phi(\alpha,\beta) = E\left[\exp(i\alpha N(0) + i\beta N(t))\right]$, the characteristic function for N(t) is simply $\Phi(0,\beta)$. At present, the BBN program computes only the one-dimensional density by applying an FFT to the characteristic function of N(t).

2.3.7 Output and Analysis

The model output consists of the one-dimensional, discretized probability density function for noise intensity. The dynamic range can be 50-60 dB. All first order

moments can then be found directly. The model does not produce sample paths or any higher order statistics at present; however, the two-dimensional (in time) density and corresponding second order statistics (e.g., autocorrelation function) will be the outputs of a future version.

2.3.8 Computer Implementation

The BBN model is coded in FORTRAN and implemented on the CDC-6000-series computer. For a typical run, to determine the one-dimensional density, the calculation requires a 10-second FFT and a total time of about one minute on the CDC 6400 ($10). The amount of time for computing the two-dimensional density is expected to be large.

2.3.9 Evaluation

Comparisons of model output with experimental data (from LAMBDA) has been proposed; but has not yet begun.

2.3.10 Significant Advantages and Disadvantages

Like the BTL model, the BBN approach provides an analytic determination of the noise density function.

Carefully chosen cases can be studied to determine the bounds and driving parameters for the noise fluctuations.

The use of general source-intensity and ship traffic models are special features of the BBN program.

The model requires the manual construction of ship scenarios and input of TL and other data. The most significant shortcomings are the lack of higher order statistics and the ensembling problem discussed in Section 1 and in connection with the USI and BTL models.

2.4 WAGNER MODEL

2.4.1 Background

Name: (Wagner Associates' Noise Model) (WAGNER)

Developer: Daniel H. Wagner, Associates,
Bernard J. McCabe

Sponsor: Office of Naval Research, Code 431

Previous Applications: Sonobuoy Problems

Published Documentation: Reference D-1

2.4.2 General Approach

The WAGNER model was developed for the sonobuoy problem and hence does not explicitly predict beam-noise statistics. It is included in this survey because it provides analytical results which supplement those of the other models and because it could potentially be modified to produce array noise data. Furthermore, the model considers not only the temporal correlation of ship-generated noise, but also the spatial correlation of average intensities for distributed sensors.

The WAGNER model actually includes three different approaches: two of them are Analytic and complementary,

while the third is Brute Force and based on the analytic formulation. Unlike the previous models, the analytic approaches are not computer-coded to yield density function, etc., but rather are used to provide characteristic functions and approximate results which in turn can be used to obtain simplified models and insight into the noise process. The Brute-Force model will be described here only in terms of its analytic basis.

The WAGNER approach is based on equation (1-1), but is distinguished in the treatment of the shipping scenario (as are the other models reviewed above).

2.4.3 Model for Ships

The two WAGNER ship models are termed: "Poisson" and "Bounded" noise processes.

Poisson: At $t=0$ the noise sources are distributed according to a 2-dimensional (spatial) Poisson process with intensity (density):

λ = mean number of ships per unit area.

This means that the number J of ships in a region of area A is a Poisson variable with parameter λA:

$$P(J=k) = e^{-\lambda A} \cdot (\lambda A)^k / k! . \qquad \text{(D-1)}$$

Moreover, the numbers of ships in two disjoint regions are independent Poisson variables; and finally the ships in a region are uniformly and independently distributed over that region.

Bounded: At time t=0, a fixed finite number of ships are selected independently from a uniform distribution over a bounded region.

Notice that the Poisson process is similar to the USI model in that the ships are uniformly distributed in a region and that the ship count is Poisson. On the other hand, it assumes an unbounded domain and constant density over that domain. The author of the WAGNER model notes in Reference D-1 that the Poisson process is useful for obtaining theoretical results while the Bounded process is needed to simulate real environments.

For either process, initial ship courses are uniform random variables on (0,360), sampled independently for each ship. Likewise, there is an input ship-speed distribution and a source-intensity distribution from which samples are taken independently for each ship. Once chosen, those variables remain constant in time, with the exception that in the Bounded process ships reflect from the boundary, with angle of incidence equal to angle of reflection. All ship sailing is "rectangular," i.e., as if on a flat earth.

2.4.4 Model for Transmission Loss

Transmission loss is a deterministic input, depending only on range. No azimuthal dependence is allowed, nor are the effects of vertical arrival structure, coherence, etc. included.

2.4.5 Receiver Model

The receiver is assumed to be an omnidirectional hydrophone, fixed in location. Its response is a deterministic input, which, together with the TL and source level, accounts for temporal processing. For the WAGNER analytic approach, the ensembling problem discussed above is present.

The results for spatial correlation are for two separated omni phones. The correlation is in intensity, so that relative phases are not required.

2.4.6 Details of the Calculation

The calculation of the noise process is based on equation (1-1):

$$N(t) = \sum_{j \in J} SL_j \cdot T_j(t),$$

where J is a countable index set. Reference D-1 first shows that for t fixed and $T(r_j)$ equal to the transmission

ratio from the receiver to a sample from the spatial Poisson process at range r_j, the characteristic function for $N(t) = \sum_{j=1}^{J} SL_j T(r_j)$ is

$$\Phi(w) = \exp\left\{2\pi\lambda \int_0^\infty \int_0^\infty (e^{izwT(r)}-1)\,r\,dr\,dF(z)\right\}, \quad \text{(D-2)}$$

where F is the common distribution function for SL_j.

It follows from (D-2) that when

$$\hat{T} = \int_0^\infty rT(r)\,dr < \infty, \quad \text{(D-3)}$$

then

$$E(N) = 2\pi\lambda E(SL)\cdot\hat{T} < \infty \quad \text{(D-4)}$$

and

$$\sigma_N^2 = 2\pi\lambda\, E(SL^2) \int_0^\infty rT^2(r)\,dr < \infty. \quad \text{(D-5)}$$

The formulas (D-2), (D-4), and (D-5) are quite useful in estimating first-order statistics for N(t).

McCabe (Ref. D-1) also shows that N(t) is stationary for the Bounded process on a rectangle and for the Poisson process. He then proposes several theses:

(a) Although no analytic method has yielded an autocorrelation function for N(t), Monte-Carlo samples for a smooth TL (with convergence zone structure) suggest that noise levels N(t) (in dB) have a nearly exponential

autocovariance function, of form

$$C(t) = \sigma^2 \exp(-t/\tau). \qquad \text{(D-6)}$$

(b) In the sample replications, the "decorrelation" times, τ, for (D-6) agree well with

$$1/\tau \simeq (1.5)\ \bar{v}\sqrt{\lambda} \qquad \text{(D-7)}$$

where $\bar{v}$ is average ship speed and λ is the Poisson ship density (ships per unit area). This formula can be explained by the argument that the decorrelation time should be related to the waiting time for the "nearest-neighbor" ship to be replaced. Nearest neighbor changes occur every $1/\bar{v}\sqrt{\lambda}$ time units in the case that ships are uniformly distributed and move at average speed $\bar{v}$.

(c) The noise level $\tilde{N}(t)$ (in dB's) is approximately Gaussian (all dimensions). The author quotes a central-limit theorem of Marlow (Ref. D-2).

(d) Finally, since $\tilde{N}(t)$ is stationary, nearly Gaussian, and has an autocovariance function which is approximately exponential, the author concludes that the process is approximately Gauss-Markov (by Doob's Theorem, Ref. D-3).

If the last proposition were valid, then the noise time series could be simulated very easily and inexpensively

(compared to the Brute Force methods or other Analytic methods). Like the BTL asymptotic limit, this approach merits further investigation, especially for possible extension to the beam-noise problem.

Reference D-1 also deals with the spatial correlation of ambient noise. A formula for the (0 time lag) cross-correlation of N(t) at two separated points is derived for the Poisson process. It does not depend on the values of λ (density of ships) or the source-level distribution, but is driven by the TL. For the noise levels ($\tilde{N}(t)$), it is shown that under certain conditions the same conclusion holds (correlation depends only on TL). Monte-Carlo simulations suggest that significant variations in TL (e.g., convergence zones) cause the spatial correlation to tend to zero quickly (i.e., within a short distance).

The WAGNER approach includes a method for simulating the noise for a field of omni sensors. It involves the construction of a set of Gauss-Markov processes which have the proper spatial correlation.

2.4.7 Output and Analysis

The general approach provides formulas for the one-dimensional characteristic function, the first two

moments, and the autocorrelation function for the omni noise intensity. If the Gauss-Markov approximation is valid, then formulas for higher-order statistics and efficient simulation routines for the noise levels are available.

2.4.8 Computer Implementation

These are routines simulating the Gauss-Markov process and the Brute-Force method (not covered here). Moreover, a computer program for calculating the spatial correlation is available. A typical run with 1000 Poisson samples and correlation calculated at 5 nm increments from 0 to 100 nm costs about $50.

2.4.9 Evaluation

The results have not been compared with measurement data.

2.4.10 Significant Advantages and Disadvantages

As discussed in 2.4.1, the WAGNER model(s) has limited direct applicability to the beam-noise problem. It assumes an omni sensor and a homogeneous ship distribution. There are however useful analytic results which, as in the case of the BTL model, should not be ignored in the synthesis of an approach to predicting beam-noise statistics.

2.5 NABTAM

2.5.1 Background

Name: (Narrow Beam Towed Array Model) (NABTAM)

Developer: Raff Associates: W. Galati, E. Moses, R. Jennette. (Operations Research, Inc., Underwater Systems, Inc.)

Sponsor: Office of Naval Research (Code 431), LRAPP, NORDA

Previous Applications: Studies for LRAPP, DDR&E, and ONR 431

Documentation: In Preparation (Reference E-1)

2.5.2 General Approach

NABTAM is a Brute-Force model designed to predict the response of a horizontal line array to wind-generated noise, surface ships, and a target at a single frequency in the range of 10-1000 Hz. The wind-noise and target signal do not change in time. The time-dependent

surface-ship noise is calculated from equation (1-1), and the remainder of this description of NABTAM concentrates on that aspect of the model.

Some attributes which distinguish NABTAM from most of the other Brute-Force models are:

(a) The transmission loss from source to receiver is calculated within the program. It is a ray-trace routine for a range-independent environment.

(b) A version of the program (maintained by ORI) performs "near-field" corrections, i.e., it calculates array response for cylindrical wavefronts from nearby sources.

(c) The TL and receiver models take into account the vertical arrival structure of the noise intensity.

(d) Beam noise for multiple array locations, depths, and orientations can be calculated in one model run (i.e., for the same ship field). Beam patterns can be calculated internally.

The model is designed to generate a single realization of the noise time series for one or several

array beams. (Monte Carlo simulations are not generally performed, nor is code structured to produce the ensemble statistics). Initial ship locations are inputs. Ship tracks are chosen from probability distributions, but remain constant for the duration of the replication. All other parameters (TL, receiver response, source levels, array location) are constant in time and deterministic.

NABTAM is programmed in FORTRAN IV and installed on a number of computers, including the CDC 6600 at Eglin AFB.

2.5.3 Model for Ships

All surface ships are assumed to have the same source level, as determined from the Ross and Alvarez "normal merchant ship" (Ref. E-2). This level is constant in time, and depends only on acoustic frequency. The source intensity does not depend on ship speed or on transmission angle.

Initial ship locations are a deterministic input. There is no real limit to the number of ships allowed, but no new ships can be created after the

initial time step. The initial ship courses and speeds can be user-specified or they can be drawn from random populations. In the latter case, the parameters are determined independently for each ship, with the course taken from a uniform distribution over a specified set of angles and the speed approximately normal (mean and variance are inputs). Once established, ships travel on tracks determined by d(Latitude)/dt and d(Longitude)/dt constants. Hence, even speed is not necessarily constant. If a ship leaves the basin area, it is not replaced.

There is no mechanism for doing replications, except to rerun the model.

2.5.4 Model for TL

NABTAM is the only noise model reviewed here which has its own internal TL routine. The program is structured in such a way that multiple receiver depths can be treated in one run and vertical arrival structure is taken into account. Hence, the TL as a function of range, depth, and vertical arrival angle is required. The program actually precalculates the ray-trace parameters as functions of vertical angle and can thus

generate TL for each source location at each time step (but for a single frequency).

The TL model is based on geometric acoustics, with no corrections for diffraction. It assumes a range-independent environment: sound speed, water depth, and boundary losses do not change in range. The sound speed profile is linearly segmented in depth. Rays are traced according to Snell's Law from the receiver depth in 1° vertical-angle steps for one cycle. If the 1° increments are not sufficient (determined in the intensity calculation), then additional rays are traced in the angular regions when they are needed. Rays are classified according to ten families (e.g., RR, RSR,...) and the range at which the source depth is crossed is stored. The spreading loss is calculated for each path from the usual expression

$$-10\log \frac{\cos\theta}{R\frac{dR}{d\theta}\sin\theta_0},$$

where R is range, θ is receiver angle, and θ_0 is source angle. The value of $dR/d\theta$ is estimated from an interpolation between rays of the same family which bracket the source range at the source depth. This is the approach

used in many of the early ray-trace models (e.g., FAST NISSM (SHARPS II) or RP-70), but has much less precision. The intensity becomes infinite at caustics (where $dR/d\theta = 0$), and the model uses preselected truncation. All paths are added on a random-phase basis so that detailed multipath interference and surface-image interference are not predicted. Individual arrivals at the receiver are collected and summed in vertical-angle bins so that TL as a function of vertical angle for the range to the source is available for the calculation of array response.

The TL is deterministic and time-invarient.

2.5.5 Receiver Model

The program can calculate the array-response time series for multiple receiver locations and orientations, using the same source field, in one program execution. Receiver locations, depths and beam patterns are deterministic program inputs which remain constant once specified. Each receiver is an array whose response to plane-wave* arrivals is characterized in terms of beam patterns, accounting for vertical and azimuthal angles, main beams and sidelobes. All energy is assumed to arrive as plane

*The ORI version of NABTAM models the near-field response with cylindrical wavefronts.

waves, distributed in vertical angle, but perfectly coherent and undistorted. The arrivals from a given source (as calculated from the TL routine) are sorted according to vertical angle and "convolved" with the beam pattern.

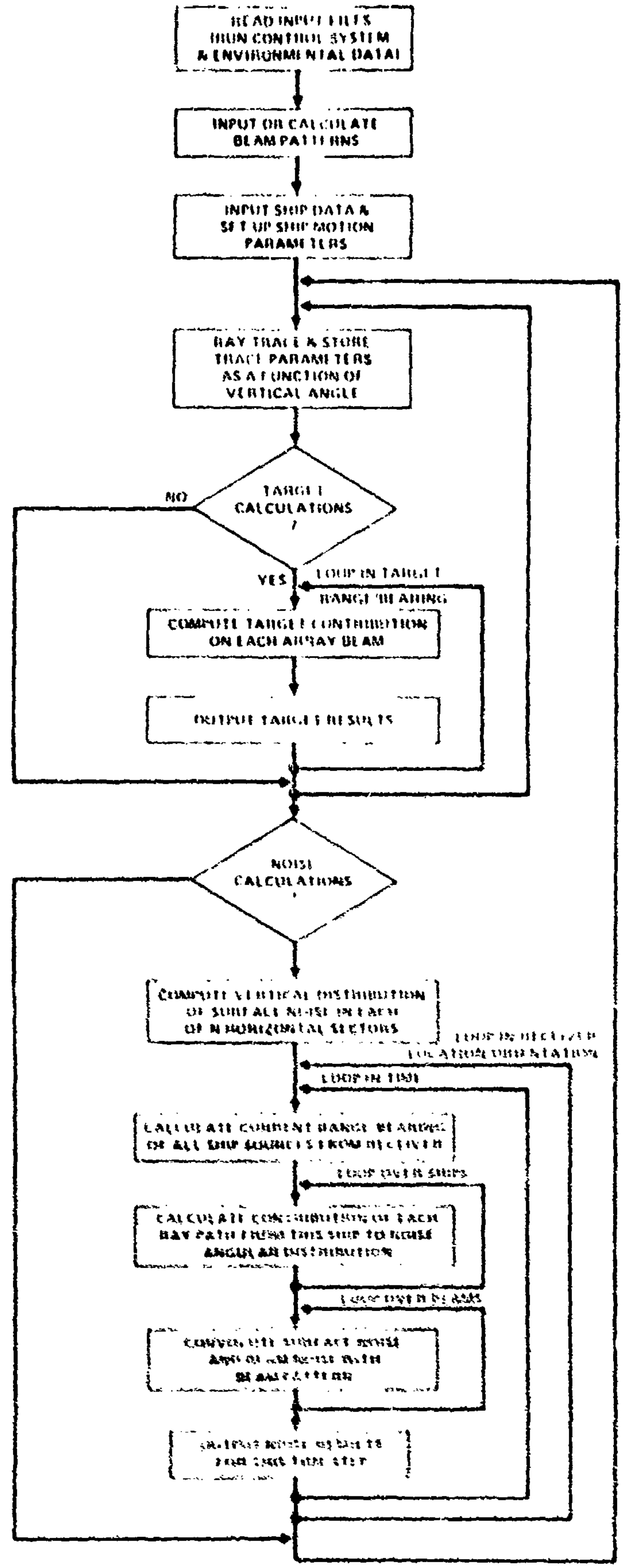
For user convenience, NABTAM has routines which calculate beam patterns for uniformly-spaced, horizontal line arrays.

2.5.6 Details of the Calculation

Once the receiver parameters, shipping field, environmental inputs and array response functions are specified, the noise is calculated at discrete time steps according to equation (1-1). Readings are taken at pre-specified time points for a selectable time span. The ship positions are tracked automatically in time and are the single cause for the time dependence of the beamformer output.

The flow of the computer program is shown in Figure E-1.

We note that wind-generated noise is a time-independent contribution added to the ship-noise field. The model treats wind sources as continuously distributed, uncorrelated point sources at the ocean surface. Provision is made to divide



NABTAM Program Flow

(Courtesy of E. Moses)

Figure E-1

the surface into angular sectors, each with specified radial extent. The contributions in each horizontal sector are computed in one-degree vertical steps, using a technique based on an approach suggested by Talham (Ref. E-3), which permits the contribution at each vertical angle to be computed from a closed form expression. The resulting noise intensity is thus a function of both horizontal and vertical angle.

Finally, the NABTAM model is structured to produce array response to fixed targets, as well as beam-noise time series. In the former application, the usual program operation is to calculate the array response for a set of target ranges and bearings, specified relative to the array. For the latter case, the receiver location and depth can be varied but the noise source (ship) locations at each time step are fixed. Combining the two sets of results permits estimates of signal to noise ratio as a function of both array and target position, while avoiding the massive number of runs required to handle each target-receiver position combination as an individual model calculation.

2.5.7 Output and Analysis

The output of the NABTAM models consists of a beam-noise time series for each beam pattern (e.g., for several

steering directions), for a single frequency, as a function receiver location. No other analysis is performed, although a time-series package (e.g., as in DSBN) could clearly be used to generate statistics of the model output. As noted above, the model can also predict wind-noise and target-signal levels (both independent of time) at the array output, and combine them with the ship noise to yield signal-to-noise ratios.

2.5.8 Computer Implementation

The NABTAM model is programmed in FORTRAN IV. It has been run on GE-635, CDC 6000-series, and other computers. The shipping parameters (and beam patterns, if not for specific line-array types) are user inputs and are not automatically generated. The program is overlaid and the core storage requirement is about 10K words. If it were not overlaid, about 13K words would be needed.

Costs depend on the number of ships, beam patterns, time steps, time span, etc. As an example, one time step for a large number of ships and five beams took 9 CDC-6400 seconds ($0.75). A calculation of beam noise for array locations and hundreds of surface ships for a limited number of time steps

can cost $100 or more. If the program were not overlaid, these costs would be reduced. Also note that NABTAM calculates TL internally, an important consideration in comparing noise-model computer costs.

2.5.9 Evaluation

There has been no formal evaluation of the NABTAM model. Comparisons were made, but not documented, several years ago with Ionian Basin (Med) and LRAPP omnidirectional noise data. The levels predicted were lower than measured by several dB, but trends in time were reportedly simulated accurately.

2.5.10 Significant Advantages and Disadvantages

Some of the attributes which distinguish NABTAM from other Brute-Force models are:

(a) The three-dimensional distribution of energy with angle at the receiver is calculated for each noise source. Hence, the time-dependent noise output of a volumetric or vertical line array can be predicted. Most important for this review, the beam output of a horizontal line array, when steered to off-broadside directions, can be computed with multipath "beam-splitting" properly accounted for.

(b) The program is structured to treat multiple receiver locations and response patterns with little computational redundancy.

(c) Array output for wind noise and targets can be calculated in the same execution as that for ship noise.

Among the limitations intrinsic to NABTAM are:

(a) The surface ship model will eventually break down as ships leave the basin of interest; the ship paths and speeds are probably unrealistic. However, the initial courses and speeds can be user inputs.

(b) The internal TL model may lack the detail and accuracy needed for fluctuation studies. Range or azimuth-dependent environments (sound speeds, bathymetry) cannot be modeled.

(c) The ship source-level model is unrealistic. Since the ship speeds and lengths are at present available in the program, the inclusion of a source function dependent on these parameters could be accomplished easily.

(d) There is no mechanism for performing multiple replications and no statistical analysis routine. But again, the addition of such a package would be straightforward.

(e) The TL, receiver response, source levels, ship speeds and courses are time-independent.

The cost of running NABTAM and the other Brute-Force models is also an important consideration, and there are only rough guidelines on the number of replications required. On the other hand, NABTAM can run several receiver locations, beam patterns, etc. at one time. Finally, this and other Brute-Force models may be the most efficient means for determining short-term statistics, level crossing properties, etc.

2.6 DISCRETE SHIPPING BEAM-NOISE MODEL (DSBN)

2.6.1 Background

Name: (Discrete Shipping Beam-Noise Model)(DSBN)

Developer: Science Applications, Inc.,
C. W. Spofford, R. G. Stieglitz,
H. M. Garon, R. C. Cavanagh

Sponsor: Office of Naval Research, Code 431

Previous Applications: Studies for APL/Johns Hopkins University, LRAPP, Institute for Defense Analysis, and ONR 431.

Published Documentation: Reference F-1

2.6.2 General Approach

Just as for NABTAM, the DSBN model is a Brute-Force model based on equation (1-1). The beam-noise time series is generated from component submodels for the surface ships, TL, and receiver. The attributes which distinguish DSBN from most of the other Brute-Force models are:

(a) the surface ship model, which uses "Poisson lanes" like those of the BTL Analytic model

(b) a receiver model which can account for the vertical as well as horizontal ship signal arrivals

(c) a computer structure designed for multiple replications and multiple beam patterns

(d) an extensive statistical analysis package

The model was developed for investigating the fluctuations caused by sources moving through the TL interference patterns and beam-response azimuths, so that attention is paid to the details of the TL and the beamformer.

The model is used to generate Monte-Carlo simulations of noise time series and is quite general in its assumptions. However, TL and shipping lanes must be constructed manually and are considered program inputs. The analysis package can yield the usual first and second order (time) statistics, as well as level-crossing properties, spectra of the fluctuations, ensemble statistics over replications, beam-to-beam cross-correlation functions and spectra.

DSBN is programmed in FORTRAN IV and is presently run on CDC-6000-series computers. Cost of a 12-hour replication with 9 beam patterns and 200 ships is under $5.

Comprehensive statistical analysis of ten such replications costs about $20.

2.6.3 Model for Ships

The module which constructs surface ship positions and parameters can be viewed as having two parts. In the first part, the source levels, courses, and speeds are generated as realizations of random variables. The second part simply tracks each ship's position and computes bearing and range to the array as functions of time. All sailing is "rectangular," i.e. on a flat earth and not on great-circle routes.

The determination of the ships and their parameters proceeds as follows. The user supplies constraints:

- Shipping "lanes" are specified by the distributions of speed and course and initial position, as well as an inter-arrival time interval (expected time between arrivals of ships across a line perpendicular to the mean lane course). Lanes are of finite length and, together with the TL function, define the boundaries of the basin.

- Source levels depend on the random speed, but also on another random variable (thought of as length) whose distribution is an input. On a given lane all source-levels

are drawn independently from the same distributions. The source intensity does not depend on vertical or azimuthal transmission angle. Note that the source-level model is the same as SIAM's.

The present version of the DSBN Model uses Poisson-distributed arrival times, so that the lane is expected to have an approximately uniform distribution of ships on the lane (i.e., constant density). The program uses a random number generator and the distribution functions to produce a single replication of a shipping field with speeds, courses, locations, and source levels for each ship.

Once selected, the course, speed and source level of a ship remain constant for the duration of the replication time (e.g., 10 hours). For each subsequent replication, the selection process is repeated.

Note that the shipping model described here is the same as that of the BTL Analytic model, and in a sense consistent with that of the WAGNER model. It can also be shown that the time-independent ship locations of the USI model are consistent with this Poisson-arrival approach.

2.6.4 Model for TL

DSBN requires as input the deterministic TL as a function of range from the receiver for the proper source/receiver geometries and frequency, and for ranges to the limit of the ocean basin (the greatest distance to a target or surface ship source). The present configuration of DSBN allows for the use of the vertical arrival structure (i.e., the loss as a function of range and vertical angle at the receiver) in order to model the three-dimensional response of an array. The model can also treat TL as a function of bearing; but for more than a few different angles, running time and computer storage can be large. DSBN cannot utilize a TL function which depends on time. The incorporation of such a feature amounts to a bookkeeping problem and could be handled if the detail and computer expense were warranted.

There is no real limit to the amount of detail permitted in the TL input. For studies of source-motion-induced fluctuations caused by multipath interference, the range resolution in the TL model depends on acoustic frequency, processor integration time, and the speed of the sources (i.e., the velocity component radial to the receiver). In a special study reported in Reference F-1,

the TL sampling rate appropriate to 25 Hz, 2-minute integration times, and 15-20 knot speeds was found to be about 0.2 miles. The maximum range for ship contributions in the basin was assumed to be 500 miles. Thus, a typical TL table for low acoustic frequencies and open ocean has 500 x 5 = 2500 entries for <u>each</u> source/receiver depth combination. It should be clear that to incorporate time or bearing-dependent TL requires tables with perhaps 2500 x 10 to 2500 x 1000 entries. If arrival structure were included, multiply these figures by 10-100.

2.6.5 Receiver Model

The receiver location is fixed, and does not change with time. For the present configuration of the DSBN Model, the receiver module is simply a functional giving the intensity response of the array to plane wave arrivals (i.e., beam pattern). Since the usual problem deals with a horizontal line array, the response is often given in terms of azimuthal arrival angles. However, to investigate the effects of the horizontal array's vertical directivity away from broadside, the simulation model can accommodate a response function which depends on both azimuthal and vertical arrival angles.

The contributions at the beamformer output of the various ships contributing to the noise field are added on a random phase (incoherent) basis. All temporal processing, filtering, etc. are handled implicitly in the source level and TL functions for the basic time sample.

For computation purposes, the user specifies the fixed location and depth of the array (for the geometry of the sources and the TL) and provides up to ten array response functions corresponding to different steering angle orientations, shading, physical deformations, or whatever. The DSBN Model simulates beamformer output for each response function or beam pattern by modifying the intensity arrivals from ship sources accordingly. The code also records the number of sources on the "main beam", defined at input.

For ease of operation, two idealized array response functions are programmed as optional subroutines for DSBN:

(a) Shaded Horizontal Line Array - Azimuthal Response Only. The function approximates the response of a shaded horizontal line array (uniform spacing) with prescribed

main beamwidth and sidelobe suppression. The sidelobes have structure approximating Dolph-Chebyshev shading.

(b) Shaded Horizontal Line Array - Vertical and Azimuthal Response. As in (a), except that sidelobes are completely suppressed.

Given that undistorted plane-wave response suffices, the primary limitation of the program is that the response function and array location cannot change with time. Such features can be added with minimal modifications to simulate, for example, the response of a transiting towed array which is changing orientation and suffering from physical deformation (wiggles).

A more basic limitation of this and other models reviewed here is that the array model does not apply directly to a predicted acoustic field which has not been decomposed into plane waves (e.g., output of the PE model). The most efficient way to deal with this is to include the array response in the transmission loss by, in effect, immersing the array elements into the field and computing the beamformer algorithm directly. This has been done for a single source and could certainly be extended to the noise case.

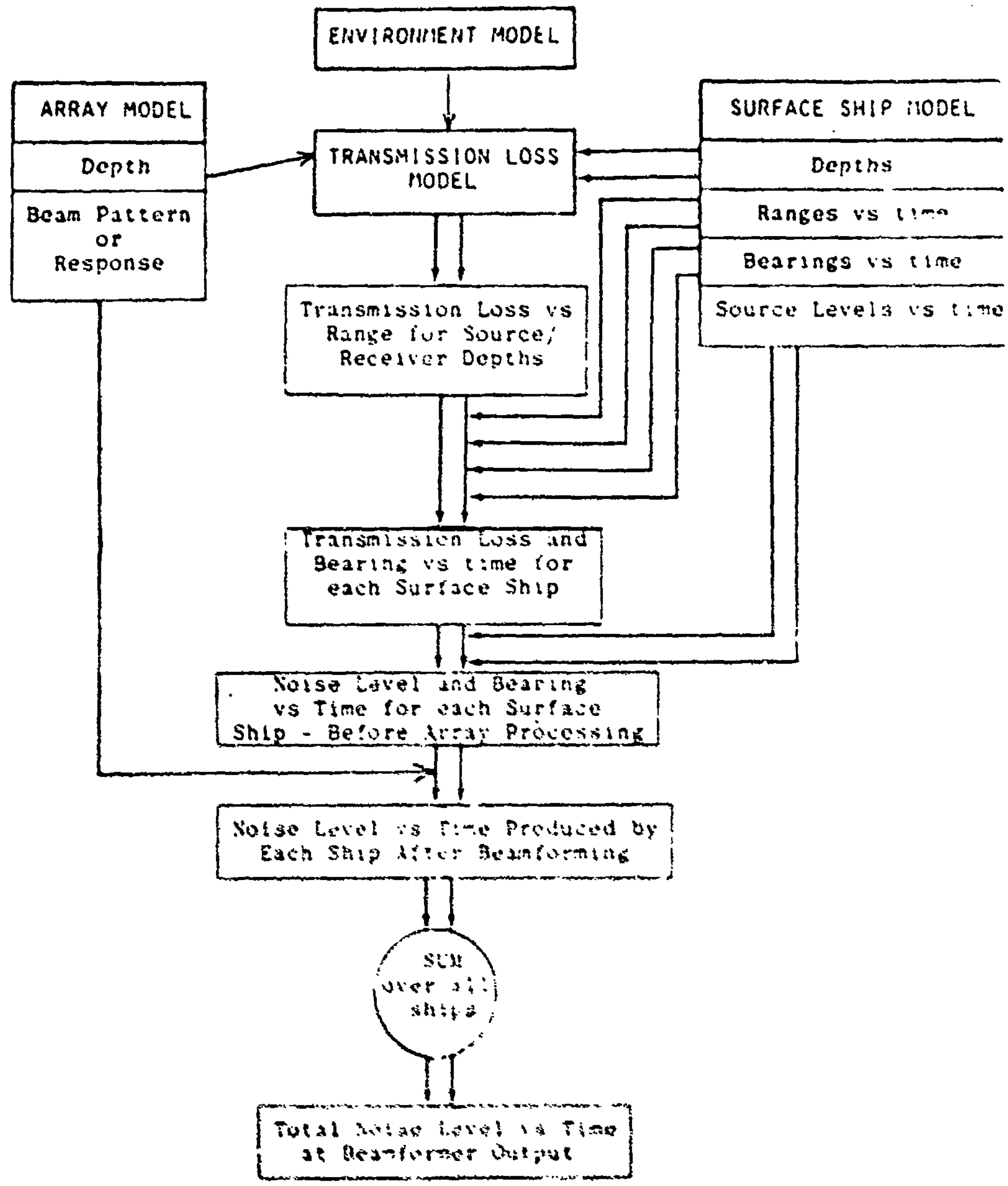
2.6.6 Details of the Calculation

Once the shipping field, TL, and array response are determined, the noise is computed at discrete time steps for each of ten (or fewer) array response functions according to equation (1-1). Readings are taken at pre-specified time points (e.g., every minute) for a selectable time span (e.g., 30 hours). The ship model provides the ship positions and source levels; the environment and TL models provide the transmission loss from each source to the receiver, and the array model provides the beam response. The modular form and flow of the computer routine are sketched in Figures F-1 and F-2. Note that only one receiver depth and frequency is treated per replication.

The statistical analysis packages operate on the simulated time series and are described next.

2.6.7 Output and Analysis

For each replication, the output of the DSBN model consists of beam-noise time series for up to ten beam patterns ("beams") and for a single frequency. The results are then analyzed by several computer packages - which operate on single or multiple replications.



DSBN Program Modules

Figure F-1

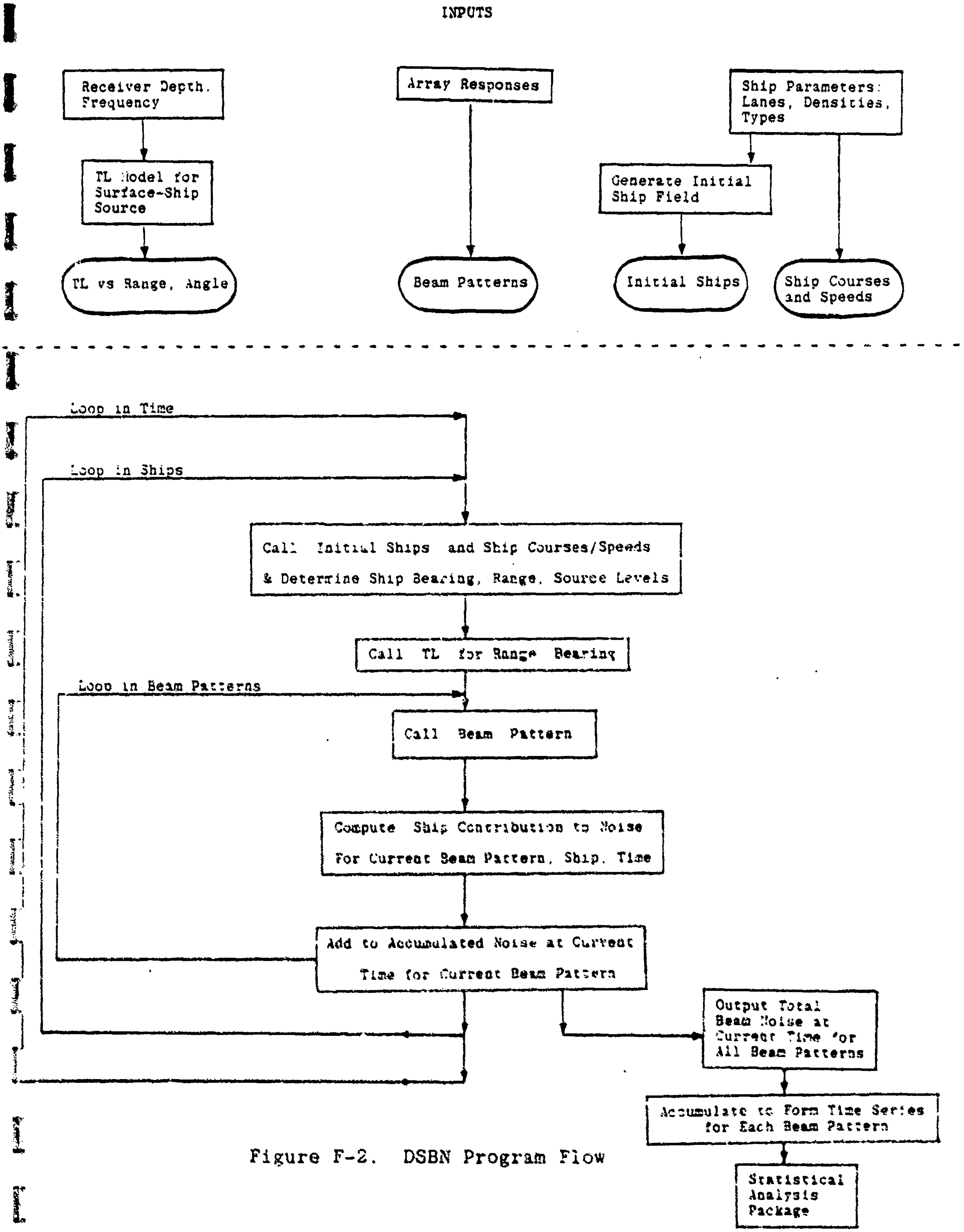


Figure F-2. DSBN Program Flow

2.6.7.1 Statistical Analysis Routine

A general statistical package has been constructed to study array time-series data. It operates on the matrix

$$N(\phi_i, f_j, t_k)$$

where ϕ_i, f_j, and t_k are interpreted as the discrete beam pattern indices, frequencies, and time steps, respectively. N is the noise level (in dB). The following calculations are performed.

(a) Histograms are constructed and plotted for any range of i, j and k to specified resolution. Likewise, the mean, variance, skewness, kurtosis, and deciles are found.

(b) For two of the three independent variables fixed.

- The series is plotted
- A "stationarity" test is performed by dividing the series into any number of equal parts and then applying (a) to each part
- The sample autocovariance function is computed and plotted
- The autocorrelation function is estimated

- An FFT is applied to the autocorrelation function to estimate the power spectral density

(c) For one independent variable fixed, the two-dimensional autocorrelation function is estimated and output in matrix form.

(d) For separation (lag) in one variable, ensembling over the second and for the third fixed, the cross-correlation function is found.

(e) For one variable fixed, one separated, and one lagged, the joint density function for the separated variables is estimated. The histogram is found and multivariate moments calculated.

(f) A Lilliefors Test (see, e.g., Ref. F-2) for goodness-of-fit can be applied to the sample histogram to find best Gaussian fit and test at confidence levels of 0.95 and 0.99.

(g) The logarithmic transformation of the Log-Normal, Non-Central Chi-Square, and Chi-Square distributions are tested against the sample distribution (for best estimate of parameters based on median and one or more other percentile points) at levels 0.95 and 0.99 with the Kolmogorov Test for fit (see Ref. F-2). Graphs of the sample and fitted functions are plotted.

(h) A simplified test for ergodicity calculates ensemble statistics in two directions (e.g., in t and then in replicas for f and ϕ fixed) and compares sample distribution functions at the 0.95 and 0.99 levels with the Smirnov Test (Ref. F-2).

2.6.7.2 Detector (Level-Crossings) Analysis Routine

A computer package has been designed to model several types of detectors. Input consists of a time series plus relevant parameters. The input time series is converted to a time history of detect/no detect states according to the following algorithms.

(a) Continuous Threshold detector

Given a time series $X(t)$, a threshold TH, and a time interval T (holding time), score a detection at time t_0 if $X(t) \geq TH$ continuously for $t_0 - T \leq t \leq t_0$.

(b) Union of Continuous Threshold detector

This is a generalization of (a) except that a sequence of thresholds and associated holding periods $\{TH_i, T_i\}$ comprises the input. Then detection occurs if the signal $X(t)$ has continuously exceeded a given threshold for the associated holding period for any member of the sequence $\{TH_i, T_i\}$.

(c) Intensity Average detector

Given a time series $X(t)$, a threshold TH, and an averaging time T, construct

$$S(t_0) = \frac{1}{N} \sum_{j=1}^{N} 10^{X(t_j)/10},$$

where the sum extends over all times t_j such that $t_0 - T \leq t_j \leq t_0$. Score a detect at time t_0 if $10 \log_{10} S(t) \geq TH$, i.e., if the intensity-averaged $X(t)$ exceeds TH.

(d) Union of Intensity Average detector

This generalizes (c). The input consists of a sequence of thresholds and associated averaging intervals $\{TH_i, T_i\}$. A detection occurs at time t_0 if the intensity average over any one of the averaging periods, T_i, exceeds the associated threshold, TH_i.

(e) N Out of M detector

Given a time history record $X(t)$, a threshold TH, and integers N and M, a detection occurs if $X(t)$ has exceeded TH for at least N out of M time points immediately preceding and including t_0.

Any one of these detectors yields a time history of detect/no detect. Various statistics are then calculated and

displayed, including the distribution of detect (holding) times, no-detect times, associated moments, order statistics, waiting times to cross a threshold, a complete history of beam-free and beam-occupied times and associated moments.

2.6.8 Computer Implementation

The DSBN model and associated analysis packages are programmed in FORTRAN IV and have been run on CDC 6000-series computers. The shipping lanes, TL, and beam patterns (if different from the two listed in Subsection 2.6.5) are program inputs and are not automatically generated.

Costs depend on the number of replications, ships, beam patterns, time period and sampling rate, TL detail, etc., and of course on the analysis. Examples:

- 200 ships, 12 hours, 2 minute samples, 9 beam patterns, 1 frequency, 2 nm average TL, horizontal response only: $5/replication

- The same case for 10-minute sampling: $1/replication

- Analysis of 8 12-hour replications such as given above (see the Table of Section 3) $20.

Core for such cases is typically under 100K (octal) or 32K (decimal) words.

2.6.9 Evaluation

Outputs of the DSBN model are at present being compared with Square-Deal and other measurement data for which there are shipping and environmental data. No conclusion can be made at this time.

2.6.10 Significant Advantages and Disadvantages

Since DSBN was designed to investigate detailed beam-noise fluctuations caused by source movements, it has such special features as: a computer structure which accomodates multiple beam patterns and replications, a receiver model that can simulate multipath beam splitting, an extensive time series analysis package to generate first and second order distribution functions and moments as well as level crossing statistics and fluctuation spectra, with time and ensemble averaging.

The model has a number of intrinsic limitations. The Poisson ship-arrival model has not been verified; the TL, source level, etc. are time-independent; it is core-consuming to have more than a few different TL curves as

functions of bearing; only one frequency and one receiver depth are treated in a single run; the beam response functions are limited to special form. The modular form of DSBN allows for relatively easy elimination of these deficiencies.

The cost of running DSBN, and the other Brute-Force models as well, is an important consideration. Moreover, there are at present only rough guidelines on the number of replications required to obtain a meaningful statistical sample. On the other hand we note that once the shipping lanes for a basin are established, the model can be run at multiple locations without additional preparation of ship data. Furthermore, for determining the short-term statistics, level-crossing properties, etc., the Brute-Force approach may be the most efficient one.

2.7 BEAMPL

2.7.1 Background

Name: (BEAMPL) ("PL" stands for "Program Library")

Developer: Office of Naval Research (AESD),
C. W. Spofford, R. G. Stieglitz,
H. M. Garon, R. C. Cavanagh

Sponsor: Office of Naval Research (LRAPP)

Previous Applications: Studies for LRAPP, PM-4

Published Documentation: None

Current Residence: NORDA, Code 320

2.7.2 General Approach and Summary

The BEAMPL noise model is nearly identical to DSBN. In fact, the basic ideas of BEAMPL were modified and extended in the construction of DSBN, so that we limit this description to an identification of the parts of BEAMPL which differ from DSBN.

- Ship source intensities are deterministic constants for each class of ship.
- Ship lanes and movements are as in DSBN except that all ships in a lane have the same deterministic constant speed.

- TL is independent of azimuth and the effects of vertical arrival structure are not included.

- The receiver module differs from that of DSBN in that it allows only one beam pattern, which depends only on the azimuthal arrival angles and has "spotlight" response (the response is unity on the prespecified main beam, and zero elsewhere).

- The output is the same as for DSBN, but the analysis packages are limited (see the Tables in Section 3).

- The computer routine for BEAMPL is substantially different from that of DSBN and is somewhat less efficient.

2.8 SIAM I

2.8.1 Background

Name: (Simulated Ambient Noise I) (SIAM I)

Developer: Naval Research Laboratory,
Samuel W. Marshall, John J. Cornyn

Sponsor: Office of Naval Research,
LRAPP

Previous Applications: Evaluation with IOMEDEX and other data for LRAPP

Published Documentation: References H-1 and H-2

2.8.2 General Approach

There are two models which share the name "SIAM."* In this section we consider the earlier version, and call it "SIAM I" or just "SIAM." The model is not actively used at the present time, but it has features worth reviewing. In the next section, the successor, called "SIAM II," will be described, it is substantially different from SIAM I.

*The name "SIAM" originally referred to a driver for the NRL model which randomly initializes the shipping parameters, controls the Monte-Carlo simulations, and calculates the ensemble statistics. We have used "SIAM" here as the name for the entire noise routine.

SIAM is a Brute-Force model designed to predict ship-generated noise over the band 20-120 Hz. It is based on Equation (1-1). The beam-noise* time series are calculated with component submodels for the ships, TL, and receiver. Notable is the ship scenario in which ships travel on specified courses, but reflect from the basin boundary and return (as in the WAGNER Bounded noise process). Initial ship courses, speeds, source levels are input or selected from distributions, but remain constant thereafter. It is of special interest that the TL has a random component (as in the USI model) which is chosen independently for each source and each time step from a common distribution. The model employs great-circle geometry and can predict the simultaneous output of several different deterministic and time-independent array-response* functions. Standard operating procedure for SIAM is to generate many replications, so that ensemble statistics are emphasized.

The model has been run on the CDC 3800 computer at NRL and is programmed in FORTRAN IV.

*As noted below, only idealized "SPOTLIGHT" beam patterns are used.

2.8.3 Model for Ships

A finite basin is defined in advance, using a maximum of 100 points to define the boundary vertices. Then ship locations, courses and speeds are initialized by class either deterministically or from random distributions. Once these parameters are established, the ships travel on great-circle paths at constant speed and with constant source level. When a ship encounters the basin boundary, it is reflected specularly.

The source intensity is a random variable for each ship and is determined from a distribution appropriate to its class. It depends on class, frequency, speed, and length, the latter two of which are uniform or normal variables. Default values for source level at 50 Hz are

$$10 \log (SL) = SL_0 + 60 \log (V/\bar{V}) + 20 \log (L/\bar{L}) \text{ dB}$$

where SL_0 is normal with mean 160 and $\sigma = 3$ (dB)

$\bar{V} = 16$, V normal with mean 16 and $\sigma = 5$ (knots)

$\bar{L} = 525$, L normal with mean 525 and $\sigma = 170$ (feet),

Source levels are independent of aspect, vertical angle, and time. A maximum of 250 ships is allowed.

2.8.4 Model for TL

SIAM requires as input a deterministic, time-independent TL as a function of range, azimuth, frequency, and receiver depth. In lieu of a user-specified table, the program can generate TL of form A+BlogR. The model uses a special: "logarithmic" routine for interpolating TL in range and azimuth. Moreover, all geometry is spherical. The only limit in the amount of detail permitted for the TL input is one of computer core and running time.

Current restrictions are:

- a maximum of 10 TL-versus-range curves for each frequency and receiver depth
- a maximum of 576 points for each TL curve
- a maximum of 30 frequencies, 29 depths each

SIAM also adds a random fluctuation component to the TL. The values are selected independently at each time step from an input distribution (default is a normal distribution with mean zero and σ = 1.5 dB).

2.8.5 Receiver Model

The receiver location is an input which does not change with time. The model is designed to give the response of an idealized horizontal array, but does not account for vertical arrival structure for off broadside steering angles. The array response is treated as a "spotlight" beam pattern: with unit intensity responses on the "main beam" and zero elsewhere. The model assumes that all energy arrives as horizontal plane waves, perfectly coherent and undistorted, from the source's azimuth. Contributions from the various ship sources are summed on a random phase basis (incoherently) and the effect of temporal processing, filtering, etc. on a basic time sample are included in the source level and TL functions.

SIAM is structured to yield simulations of the simultaneous noise output for multiple beams. Hence, the input consists of several beam patterns, i.e., several main beams, but no sidelobes.

2.8.6 Details of the Calculation

Once the ships, TL, and array response are established, as discussed above, the noise is computed at discrete

time steps according to equation (1-1). Readings are taken at specified time points for a selectable time span but with a maximum of 4000 samples per case. The computer flow is summarized in Figure H-1.

2.8.7 Output and Analysis

The basic SIAM output is the time series of noise as a function of beam, frequency, and depth. The usual operating procedure is to perform many replications over the various fluctuators (TL, SL, ship parameters). A special analysis routine prints or plots ship locations and noise time series, and calculates the "grand ensemble" moments of the noise, i.e., averages are over time and replication, as well as the sample one-dimensional density function (all for noise levels in dBs).

The program yields complete histories of ships (including plots) as well as percentages of beam-free and beam-occupied times. A valuable feature of the SIAM output is the identification of the ship which makes the greatest contribution at each time step and a list of ships in order of their importance over a specified time interval.

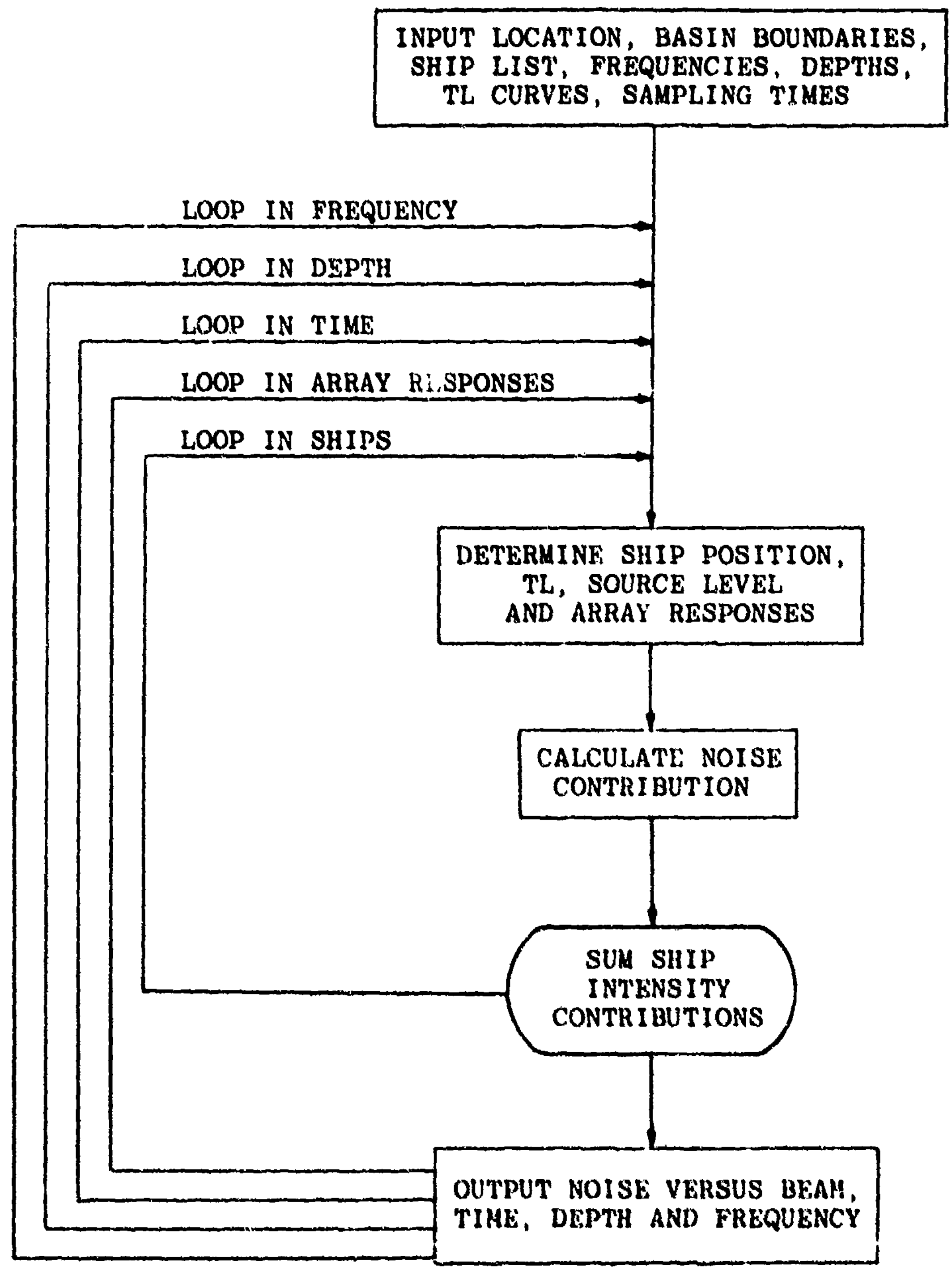


Figure H-1. SIAM Flow Summary

Guidelines, based on experimental runs of SIAM for canonical cases, have been established for the number of Monte-Carlo replications required to obtain "convergence."

2.8.8 Computer Implementation

SIAM is programmed in FORTRAN IV and has been operated on the NRL CDC 3800 computer. The shipping parameters, TL, beam patterns are program inputs and are not automatically generated.

Costs depend on the number of replications, frequencies, depths, beams, ships, sample times, etc. The author reports that a typical run, as reported in Ref. H-2, would require no more than 5 or 10 minutes on the CDC 3800 computer.

2.8.9 Evaluation

SIAM model output has been compared with beam-noise data from controlled experiments (see Ref. H-2). The uncertainties in the measurement data, input data, and analysis preclude a thorough evaluation of the model but agreement between measured and predicted noise distribution functions was generally good.

2.8.10 Significant Advantages and Disadvantages

SIAM I was designed to generate Monte-Carlo estimates of one-dimensional distributions of noise. Its treatment of ship movement and its computer structure are tailored to this application. Noteworthy features are the great-circle ship sailing and the additive TL fluctuation term.

The model has certain intrinsic limitations. The deterministic part of the TL, the receiver location and response, the source level, ship speeds and courses are all independent of time; the vertical arrival structure at the array is not accounted for; computer storage limits the number of ships; the ship reflection model may be unrealistic; the analysis package is limited. Furthermore, the addition of a TL fluctuation term independently at each time step precludes the possibility of calculating realistic temporal autocorrelation or higher order moments. Each of these could be eliminated in a straightforward way.

The cost of running SIAM, and the other Brute-Force models as well, is an important consideration. However, the model can be run for several frequencies and receiver depths and beams at one time, and once the ship

field is input, it can be used for other receiver sites in the basin. Finally, for determining short-term statistics, level crossing properties, etc., the Brute-Force approach may be the most efficient one.

2.9 SIAM II

2.9.1 Background

Name: (Simulated Ambient Noise II) (SIAM II)

Developer: Naval Research Laboratory,
S. C. Wales, S. W. Marshall

Sponsor: Office of Naval Research, LRAPP

Previous Applications: Evaluation with EPAC and other data for LRAPP (References A-1, I-1 and I-2)

Published Documentaion: In preparation (User's Manual/JUA Article). See Reference I-2.

2.9.2 General Approach

SIAM II is the successor to SIAM I (Section 2.8). It is a Brute-Force model, designed to provide many replications of surface-ship noise for horizontal array systems, especially narrow-beam systems. It differs from the other noise models in its approach to simulating ship traffic, but does calculate beam noise from equation (1-1).

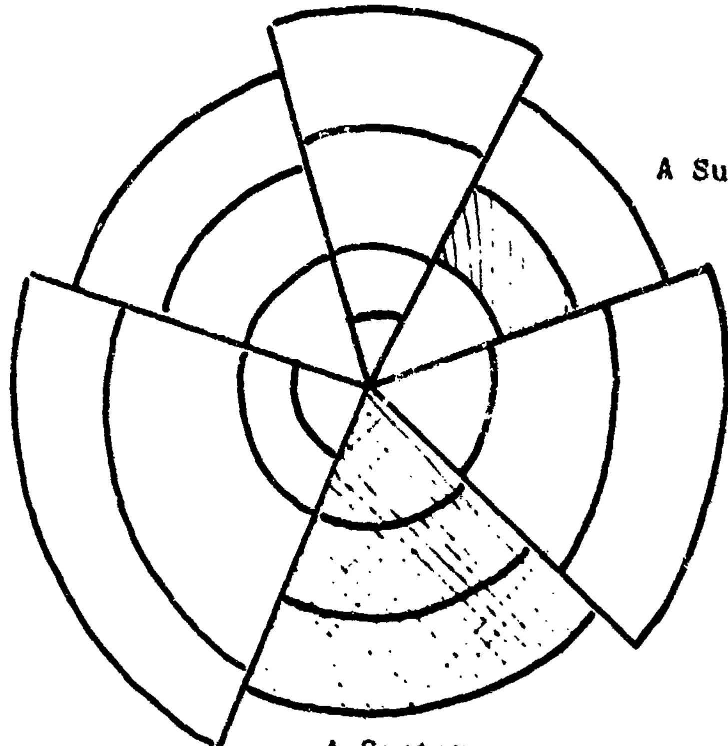
The unique aspect of the SIAM II approach is that it calculates many (32) sample time-series in one run, using a special ship-tracking routine which, in effect, cycles ships through the beams within annular regions. This is done to solve the problem of creating new ships as others leave the basin and to provide multiple samples from the same basic ship scenario. Source levels and speeds are constant in time, but initialized from random populations.

The TL is an input table for each azimuthal sector, but does not depend on vertical angle. It has a fluctuation component, uncorrelated in time. The array response is modeled with a single deterministic beam pattern.

The model is implemented on a PDP 11-45 computer and is programmed in FORTRAN. The present configuration makes for lengthy running times and tedious data entry.

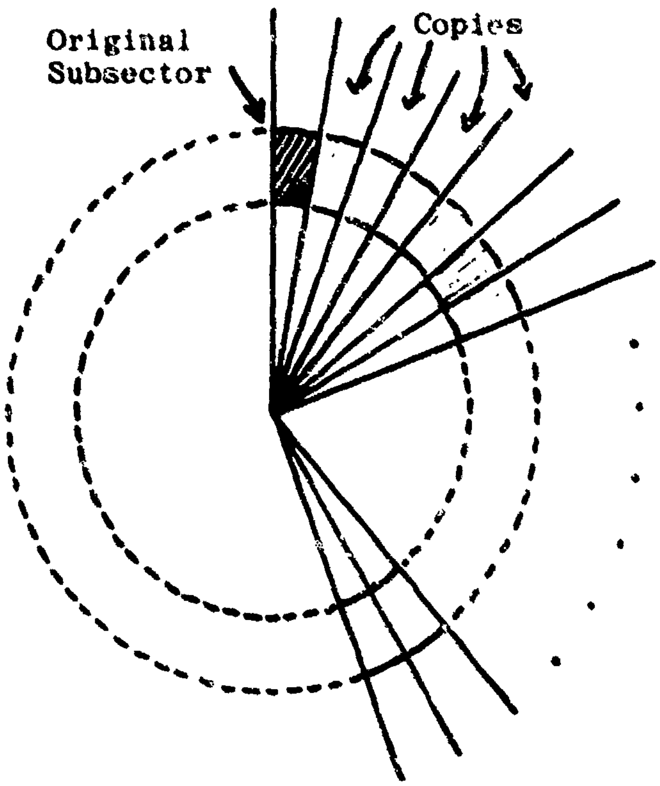
2.9.3 Model for Ships

The SIAM II ship traffic model is different from all of the others reviewed here, and we spend some time describing it. An ocean "basin," centered at the fixed receiver location, is divided into sectors and subsectors as shown below.



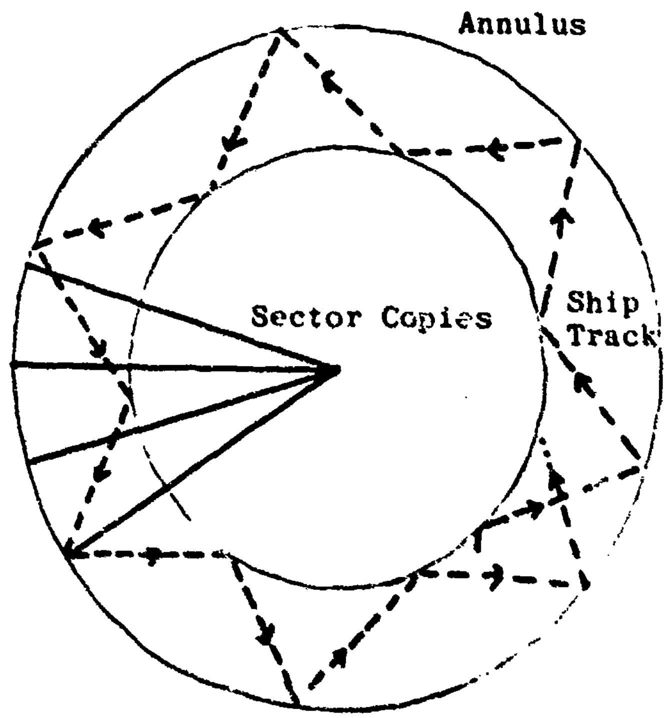
The sector aperture is determined from the array beam pattern (e.g., corresponding to the main beam width and perhaps principal sidelobes), while the subsector extent is chosen to be consistent with shipping lane widths (usually 50-200 nm) and the basin environment. A maximum of 16 sectors is allowed, but the number of subsectors is unlimited. All geometry assumes a flat earth. As discussed below, the contribution to the noise field from each of the subsectors is calculated sequentially.

For a given subsector, the computer routine then, in effect, constructs up to 32 copies of the subsector and internally generates an annulus from the copies, centered at the receiver location:



Ships are initially distributed uniformly in the annulus according to the input subsector density. Ship speeds (and lengths) are chosen independently from a nearly-normal distribution for prespecified mean and variance. Ship courses are drawn from a uniform distribution over (0°, 360°). Ship source levels may be inputs or may follow a speed/length rule as in DSBN or SIAM I. Once selected, these ship parameters remain constant for the time span of one replication

(up to 128 time steps). The ships are then tracked in time around the annulus, following straight-line paths and reflecting specularly from the boundaries as encountered:



The ship history within each subsector copy is treated as a sample of ship traffic for the original subsector, so that 32 samples are obtained at once. This is the objective of the approach. If the sector aperture exceeds 11.25^o, i.e., 360^o/32, then fewer than 32 samples are obtained in a single run and more runs are made until 32 samples are obtained. Separating the sector copies is allowed, but overlapping them may cause undesirable correlations for adjacent copies.

The above procedure is repeated for each subsector of interest. The model usually concentrates on the main lobes of an array, so that only a few sectors need be treated in a single model run. Full 360° response can, however, be obtained.

As is the case for most of the other noise models, source intensity is independent of time and the transmission angle.

2.9.4 Model for TL

SIAM II uses an input table of TL versus range for each of as many as 16 sectors, a single frequency, and one receiver depth. As an alternative, the model will generate an A + BlogR table internally for each sector. The amount of detail in the TL function is selectable, but should be consistent with the time-sampling rate, i.e., the rate at which the time series of noise is generated and the sonar-system averaging time.

As an added feature, a fluctuation component can be added to the input TL. It is chosen independently for each source at each time step from a normal distribution with zero mean and specified variance.

The program is not structured to account for the vertical arrival structure of transmission.

2.9.5 Receiver Model

The receiver location and depth are implicitly defined by the TL and ship field, and do not change in time. The receiver is assumed to be a horizontal array with response to plane wave arrivals in the horizontal plane determined from an input beam pattern. No discrimination in vertical angles is allowed. Only one beam pattern (frequency, array depth) is permitted in a single replication. As an option, a special "spotlight" mode employs a single "perfect" beam and shortens computation time.

As a ship progresses around the annulus, its contribution at each time point is added incoherently to the appropriate sector copies. Only one beam pattern is allowed for each sector, but different beam patterns may be input for different sectors and sidelobes can be included in this fashion. All temporal processing, filtering, etc. are treated implicitly in the source and TL functions for the basic time samples.

2.9.6 Details of the Calculation

The program input and calculations proceed approximately as follows:

- The basin is divided into sectors (up to 16) and subsectors (as many as required), as discussed above, oriented to the receiver location.

- The user inputs a TL table for each sector, appropriate for the single frequency, receiver depth, and surface-ship source.

- The user inputs a beam pattern, time-step increment, and number of time steps (up to 128).

- For each subsector, the user inputs the ship parameters: mean number of ships, mean ship speed and length, mean (standard) source level.

- The program begins with the first sector and its first subsector

- The subsector copies (32) and annulus are generated internally (as illustrated above). The program initializes ship positions in the subsector, ship speed, courses, and source levels - using the appropriate random-number generator.

- Each ship then moves in time in the annulus for 128 time points. The source levels, TL for the sector and range, and beam-response for the ship bearing are combined to yield 32 realizations of the ship's contribution to the noise for the current sector as a function of time. The intensity is added incoherently to a cumulative sum of noise for each time point and the first sector. These values are stored in a (copy number × time) array of up to (32 × 128 points).

- Once all ships for the current subsector have been treated, the program goes on to the next subsector, and continues until all subsectors of the first sector are completed. The result is 32 realizations of the beam-noise time series for ships in the first sector.

- Ship-noise contributions for the other sectors are then calculated in sequence in the same way as for the first sector.

- As each sector is completed, its contributions to the beam noise (32 time series) are added incoherently to the cumulative sum stored in the 32 × 128 point array.

- Basic output consists of 32 time series of beam noise, each of length up to 128 time steps, as well as ship histories.

The program flow is summarized in Figure 1-1. Notice that in the innermost loop the contribution of an individual ship is determined for the entire time span and for each of the 32 subsector copies. For this reason, present program size limits the number of time points per time-series sample to 128. Note also that only one complete beam pattern is allowed per computer run.

We emphasize that new ships and ship tracks are constructed for each subsector's contribution. Hence, there is no correlation between ships of one subsector and ships of another.

Finally, a constant wind-noise level is added incoherently to the resulting ship-noise time series.

2.9.7 Output and Analysis

The basic model output is a set of 32 beam-noise time series (or several sets of 32 if additonal replications are made). An analysis package operates on these data to yield:

- Histograms of Noise (1 dB resolution)
- Sample Distribution Functions (in dBs)

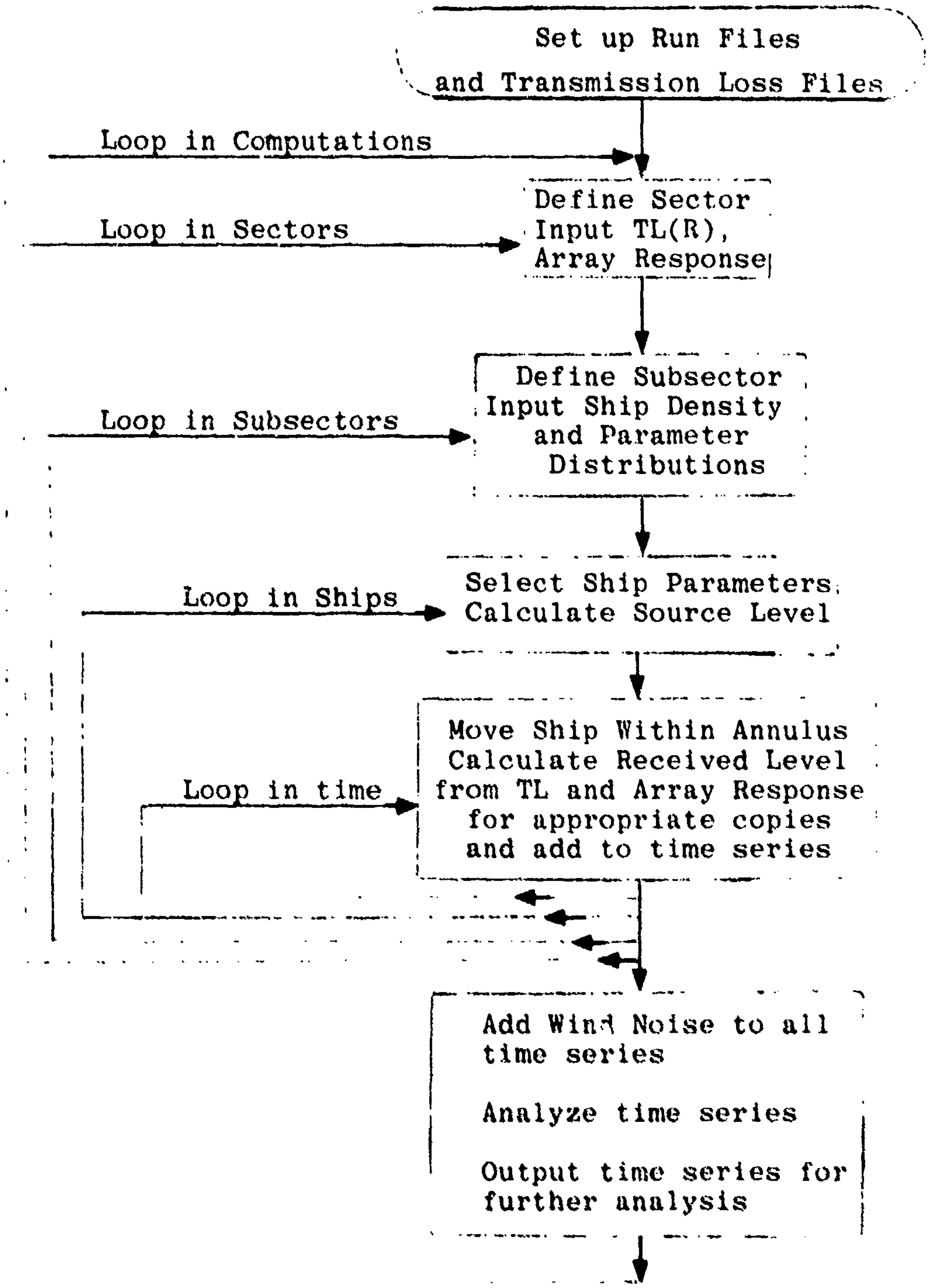


Figure I-1. SIAM II Program Flow
(Courtesy of S. C. Wales, NRL)

- Mean and Variance for the Noise Levels (dB)
- Median of the Noise Distribution

Temporal autocorrelation is not available as an integral part of the program.

Note that beam-to-beam correlation is not generally available, since only one TL, one beam pattern, and one ship density are usually run at a time. It could be obtained for cases in which beam patterns, ship densities and TL are nearly the same for the two steering directions.

2.9.8 Computer Implementation

SIAM II is programmed in FORTRAN and is presently installed on a NRL PDP 11/45 computer. It requires 26K core. Data entry (ships, TL, etc.) is from files stored on disk comprised of a main file and separate TL files. Creation of these files can be tedious.

Costs depend on the number of ships per degree, complexity of the array response, number of subsectors, etc. As an example, 25 ships, 32 copies, 2 3^{o}-sectors and 128 time points required 10 minutes running time on the PDP machine.

2.9.9 Evaluation

According to the author of the program, SIAM II has been compared with North Pacific beam-noise data and showed very good agreement. Also, see Ref. A-1, I-1, and I-2.

2.9.10 Significant Advantages and Disadvantages

Among the limitations of the SIAM II model are:

(a) The ship traffic model may be suitable for certain conditions, but does not allow for beam-to-beam correlation or the accurate simulation of ship tracks.

(b) The array response and TL models do not account for vertical arrival structure.

(c) The time series are limited to 128 sample points, by core constraints.

(d) The operation of the model is tedious.

(e) The model is in general not structured to give the details of the noise fluctuations when complex side-lobe structure or TL fluctuations are important.

(f) Only a single beam pattern is allowed (per sector) in one model run.

(g) The TL fluctuation is uncorrelated in time.

The time and cost considerations are also important, but difficult to compare with the other Brute Force models.

On the positive side, the approach is innovative and worthy of further investigation. Some, but not all, of the distinct advantages of a Brute-Force model mentioned before (e.g., short-time statistics, higner-order statistics) are to be found in SIAM II.

Section 3

SUMMARY AND RECOMMENDATIONS

The tables given at the end of this section summarize the properties of each of the nine noise models reviewed in this report. The problem now is to choose those models or parts of models for use in LRAPP efforts: area assessments, exercise planning, measurement analysis, performance predictions for fleet use, etc. In lieu of an attempt to decide here what noise statistics and type of model are needed for each of these activities, the next several subsections list some potentially useful quantities and identify candidate models for predicting them. The final subsections give general recommendations for a LRAPP approach to modeling beam-noise statistics and discuss some special problem areas.

3.1 ONE-DIMENSIONAL DENSITY FUNCTIONS AND MOMENTS, GRAND ENSEMBLE

Here is required the first-order (one-dimensional) statistics of the beam noise level or intensity, viz., the density function, percentiles, mean, variance, skewness, etc., but no temporal statistics. By "grand ensemble" is meant that the statistics are ensemble averages over all

variables which are modeled as random, e.g., ship counts, ship tracks, source level variations, etc. For all of the Analytic models, such an ensemble is probably consistent with an average over at least several days since each one of them defines variations which would take that long to occur. For the Brute Force models, time-series replications covering many days or else a number of random "restarts" is required to give such statistics.

Hence, the most efficient approach to obtaining this solution is the USI model. It is orders of magnitude faster than any of the other Analytic routines and does not rely on asymptotic limits or approximations to normally distributed variables. Certain additional work on the model seems to be in order, however:

- A computer routine to automate the input (such as FANIN) must be developed in order to make the model suitable for frequent execution.

- The Poisson ship-count assumption (consistent with WAGNER, and in a sense with BTL and DSBN) should be tested for sensitivity and reviewed in light of data (see Reference B-2).

- The unusual nature of the recursive calculation of the density function suggests that a full documentation of the underlying algorithms be reviewed by LRAPP.

- Moments and the density function should be calculated both for noise intensity units and for noise levels (dBs). This should be a trivial extension of the existing routine.

3.2 ONE-DIMENSIONAL DENSITY FUNCTION AND MOMENTS, LIMITED-TIME ENSEMBLE

In some applications, the "grand ensemble" statistics are not appropriate, and it is the short-term (say 12 or 24 hours) description of noise which is required. For example, a "grand-ensemble" calculation would not be appropriate for simulating the temporal behavior of measured noise from an experiment in which ship positions are known. The Analytic models cannot, in general, produce such statistics since they ensemble over the entire population (see Subsection 1.1 for further discussion of this problem). The BTL model or the limiting log-normal approximations of BTL and WAGNER are the only ones which produce higher order statistics and hence have the potential to provide short-term data.

On the other hand, the Brute Force models can easily produce short-term sample functions and their time-ensembled statistics. Any of the five models listed could provide a set of density functions and moments for short-term realizations.

3.3 MINIMAL TEMPORAL STATISTICS, GRAND ENSEMBLE

By "minimal temporal statistics" is meant the temporal autocorrelation function, decorrelation time, and percent of beam-free time. These can be important for detection analysis.

Of the Analytic models, only the BTL model can provide these data for the general case. Only if the Gauss-Markov approximation is valid can the WAGNER Analytic model produce autocorrelation functions without Monte Carlo replications. The USI model can estimate beam-free probabilities only, and the BBN model cannot at present predict autocorrelation functions (the two-dimensional density calculation has not yet been implemented). Hence, subject to an examination of the Poisson ship-arrival assumption, the BTL approach seems to be the leading candidate.

3.4 HIGHER-ORDER TEMPORAL STATISTICS

For certain applications the level-crossing properties of noise (e.g., the probability that noise remains below a threshold for a given time period, or the waiting time to cross a level) are required. These are in general "higher-order" statistics in the sense that a two-dimensional density does not give enough information to determine them. Among the approaches available to predict level-crossing properties, the Brute-Force models (DSBN, BEAMPL, NABTAM, SIAM I or II) would be the easiest to apply. In fact, DSBN's current statistical package described in Section 2.6 calculate level-crossing properties. The principal drawback is the expense of making computer runs for multiple replications.

The only real alternatives to the Brute-Force approach are of dubious potential:

- the BTL model - which involves calculations equivalent to generating multidimensional density functions from characteristic functions, or else use of the asymptotic limiting distribution - which still requires a correlation function,

- the Gauss-Markov approximation suggested by WAGNER - which remains to be verified for beam-noise applications.

Note also that the Analytic models will yield only grand-ensemble values, while the Monte-Carlo models can give short-term samples.

3.5 MULTI-BEAM AND MULTI-ARRAY STATISTICS

The prediction of multi-beam or multi-array statistics has its own special importance for current applications, as well as its own special problems. Of the Analytic models reviewed here, only the BTL approach considers the general case. For special canonical ship scenarios, Reference B-2 lists formlas for cross-correlation functions and asymptotic joint densities. The WAGNER model, although structured to predict spatial correlation for omni sensors, has promise for multi-array applications.

Any of the Brute-Force models can be made to predict the simultaneous noise outputs from several beams. Both DSBN and NABTAM are presently configured to do it, and DSBN has a special package which calculates cross-correlation and joint density functions for beam-to-beam correlation

statistics. The situation is different for the case of multiple array locations. Except for NABTAM, the Brute-Force models must be rerun for each new receiver location, but with the same ship field. This is straightforward for DSBN, BEAMPL, and SIAM I, but not possible for SIAM II (since the ships are oriented about the receiver location).

Since the combination of cases and model attributes are many, Table 3-1 shows the models judged to be leading candidates for each application

3.6 GENERAL RECOMMENDATIONS

From the preceding discussion it should be apparent that no single model is the best choice for all applications. Nor does it seem that pieces and parts of the several models described can be integrated into one all-purpose routine. However, it is proposed that LRAPP take the following approach:

(A) For a first look at grand-ensemble, first-order statistics, use the USI model (after automation of input, etc. listed in Section 3.1)

APPLICATION

MULTIBEAM (Common Ships), SINGLE LOCATION	MULTIBEAM, MULTILOCATION (Common Ships)	Include Beam Splitting	Include Detailed TL	Grand Ensemble	Limited-Time Ensemble	Cross Correlation	Joint Density	Simulated Time Series	CANDIDATES
X				X		X	X		BTL, SIAM I, SIAM II
X		X	*		X			X	NABTAM
X		X	X	X	X	X	X	X	DSBN
X			X	X	X			X	SIAM I, SIAM II
	X			X		X	X		BTL
	X	X	*		X			X	NABTAM
	X	X	X	X	X	X	X	X	DSBN (Multiple Runs)
	X		X	X	X			X	SIAM I (Multiple Runs)

*Internal Ray-Trace

Candidate Models for Multibeam Statistics
Table 3-1

(B) For insight about controlling parameters and to obtain bounds on temporal statistics, use the BTL analytic formulas for canonical cases. Again, some kind of automated system must be developed to generate inputs.

(C) For prediction of the detailed noise fluctuations, for measurement analyses or detection studies, use one of the Brute-Force models. It seems that a modest effort would yield a synthesized model employing automated input and statistical analysis packages plus the best features of the five models listed (e.g., great-circle sailing from SIAM I, analysis packages from DSBN, limited-time and grand ensembles, etc.).

(D) For multi-beam correlation, use BTL formulas for bounds and one of the Brute-Force models (of Table 3-1, as appropriate) for details.

3.7 ADDITIONAL REMARKS

This report concludes with a brief identification of problems shared by the reviewed models and which requires further study.

- <u>Inputs for Detection Simulation</u>

  None of the models reviewed can be used to simulate the real detection process, i.e.,

to predict signal-plus-noise in one frequency bin and an "estimate" of noise (e.g., value in another bin or average over other bins, etc.).

- <u>Noise Statistics for Time-Dependent Array Responses</u>

  In actual applications, the array may well be towed, so that then its location changes in time and its response changes in time (distortion). None of the models deal with this case. The beam-free times and other noise fluctuation properties are expected to be affected significantly by this array motion.

- <u>Ship Information</u>

  The most difficult and time-consuming task associated with producing beam-noise statistics seems to be the preparation of surface-ship densities and, especially, ship lanes. Although some automated routines exist (e.g., FANIN, the input for FANM, at NORDA) they are not widely used, and further development and evaluation are indicated.

  In addition to the ship-location problem, there remains a significant uncertainty in the prediction of source levels and directivity. Recent measurements should eventually result in better estimates of

the radiated noise. For the present, however, the Ross and Alvarez spectra of Ref. E-2 and the BBN statistical model of Ref. C-3 (which accounts for discrete components of the spectrum) are the best data available.

- <u>Noise Model Evaluation</u>

  If convincing validations (with measurements) of mean-noise models are scarce, then those for beam-noise statistics models are very rare indeed.

- <u>Wind-Dependent Noise</u>

  Little attention has been given here to the modeling of the statistics of wind-related ("surface" or "sea-state" or "wind/wave") noise, either omni or at the array output. Such noise can be important, even at low frequencies, and the problem warrants further investigation.

Summary: ANALYTIC MODELS (I)

Model	Approach	Ship Source Intensity
BBN	The method involves the direct calculation of one- and two-dimensional probability density functions by Fourier inversion of the characteristic functions. The important calculation is of the characteristic function when shipping traffic and source levels are random variables. The model is structured to provide "main beam noise" only - i.e., noise from a fixed azimuthal sector.	Ship source level is a random variable, independent from ship to ship, selectable by class, but always independent of time and azimuth and vertical angle.
BTL	The noise process is treated as "shot-noise process" by the assumption that ships travel on paths and have Poisson arrival times. Calculation of multi-dimensional characteristic functions and moments use shot-noise assumption. Fourier inversion or use of log-normal limiting distribution is often needed to obtain statistics.	Same as BBN, but all ships on a path have the same distribution of source intensity.
USI	The key to the approach is that the number of ships in a geographic domain is a Poisson variable ("spatial Poisson process"). Then the noise is a single-time sample from "generalized Poisson process." The one-dimensional density is calculated with a special iterative algorithm for which geographic domains are grouped according to contribution (per ship) to noise intensity. The method avoids characteristic functions and direct convolutions.	Same as BBN, but all ships counted by the Poisson variable have the same distribution of source intensity.
WAGNER	Two different formulations ("bounded process" and spatial Poisson distribution of ships) lead to a "generalized-Poisson process" characteristic function. Also, the approach includes a brute-force method for obtaining sample paths. A central limit theorem and Monte Carlo simulation to obtain correlation functions leads to conclusion that omni noise level (dB's) is approximately a Gauss-Markov process. A formula for the spatial correlation of noise is obtained for the general Poisson process. The model is structured to produce omni noise statistics at distributed locations.	Same as BBN, but main results assume all ships have the same source intensity distribution.

Summary: ANALYTIC MODELS (II)

Model	Ship Locations and Motion	Sound Transmission
BBN	Ships are assumed to travel in lanes or routes. The number of ships in a lane of a certain class, the source level, initial position, and course are random variables. The speed is a constant for the class, while source level distribution is the same within a class. Ships travel at constant course and speed once initialized: "Rectangular Sailing."	Transmission loss is deterministic and defined according to azimuthal sector and ranges. There are no restrictions on the amount of detail permitted. The effects of vertical arrival structure, coherence, etc., are not included.
BTL	Ships travel on "paths," which may be grouped in lanes or as isotropic fields. On a path, ships arrive at the main beam steering angle according to a Poisson rule. Furthermore ships on a path have course, speed, and source intensity drawn from the same distribution. Once initialized, a ship travels at constant course and speed: "Rectangular Sailing."	Same as BBN
USI	Since the model does not produce temporal statistics, the ships do not move in time. Input is the mean number of ships (by class, if desired) in each of many geographic domains. The number of ships in each domain and class is then treated as a Poisson variable, and those ships are assumed to have the same source level distribution.	Same as BBN, except that a TL fluctuation distribution can be defined at input for each geographic region in which ships are defined. This TL fluctuation variable is combined with the source level variable in the model calculations. The fluctuation value is independent from ship to ship.
WAGNER	The ships are distributed initially according to a spatial Poisson process, i.e., the number of ships in a region is a Poisson variable whose mean is proportional to the area of the region, or else as a bounded process in which a fixed number of ships are distributed uniformly in a bounded region. In each case, the course, speed and source level are random variables, chosen independently for each ship from the same distributions; once selected these variables remain constant in time. For the Poisson process, ships are defined on an unbounded region, for the bounded noise process, ships reflect from boundaries of the domain. Sailing is "rectangular."	Same as BBN. A single, azimuthally-independent TL is used at present

Summary: ANALYTIC MODELS (III)

Model	Receiver	Output
BBN	The receiver is a horizontal array with fixed location and deterministic, time-independent response. All energy is assumed to arrive as plane waves in the horizontal plane - perfectly coherent and undistorted. The model is structured to provide output for the main beam only (i.e., noise from an azimuthal sector). Contributions from different sources are added incoherently (random phase). Extension to predict sidelobe levels is possible - but computationally expensive. The array is assumed to be perfectly straight, horizontal and ideal in its response.	Fully ensembled one-dimensional density and moments of noise intensity in one azimuthal sector. Eventually the model will produce two-dimensional densities (in time), autocorrelation functions, etc.
BTL	Same as BBN, except that noise from the sidelobes can be predicted. The model has also been structured to produce multi-beam, multi-array noise statistics.	Fully-ensembled k-dimensional densities and moments are available. Computations become difficult for k > 3. For special cases, there are formulas for moments and correlation. The model can produce beam to beam or multiarray joint statistics. If a certain asymptotic limit applies, the noise intensity is modeled as a multivariate log-normal variable. In that case, the calculation of higher order statistics is greatly simplified.
USI	Same as BTL. However, a random array-response fluctuation for each ship group can be imposed. It is treated in the same way as the source level and TL fluctuations.	The fully-ensembled one-dimensional density function (with 1.5 or 3dB resolution) and moments of main-beam and side-lobe noise intensity are predicted. Model provides information on which ships are important to mean and variance. No higher order statistics, except percentage of beam free times, are available.
WAGNER	The receiver is an omni phone (or phones) with fixed location and deterministic, time-independent response. Extension to the horizontal array case is possible. The model is structured to produce multi-sensor noise statistics.	The brute-force implementation allows for the Monte-Carlo calculation of higher order statistics. Otherwise, the model produces the characteristic function, one-dimensional density and moments, fully-ensembled. No analytic formulas for higher order (time) statistics are given. The spatial correlation function is written in integral form and approximations are listed. When the Gauss-Markov approximation is valid, higher order statistics, level-crossing results and time-series simulations are readily available.

Summary ANALYTIC MODELS (IV)

Model	Computational Efficiency
BBN	• All input is manual. • Computer calculation of characteristic functions and Fourier inversion for one-dimensional density (50-60 dB dynamic range) takes about one CDC-6400 minute ($10). • Two dimensional statistics are expected to be calculated at much greater expense.
BTL	• Same as BBN except that the form of the characteristic function and a smaller dynamic range (30 dB) yields less expensive routine. • BTL is structured to calculate higher order and multiarray statistics. • When the asymptotic limit applies, a very efficient model results. • Typical calculation of one-dimensional density function on UNIVAC 1108 takes 60K core and 5 minutes, per shipping lane
CSI	• All input is manual, although a FANIN-type routine would help, since only ship densities are used. • TL, SL, AG and ship domains are grouped manually. • Actual computation of density function costs less than $1.00.
WAGNER	• All input is manual. Ship input is not difficult since initial distribution is uniform and courses and speeds are given by single distributions • The analytic solution for one-dimensional density requires Fourier inversion of characteristic functions (like BBN or BTL). • If Gauss-Markov approximation is valid Wagner has many closed form results and computer simulation tools.

Summary: BRUTE FORCE MODELS (I)

Model	Ship Source Intensity	Ship Locations and Motion
BEAMPL	Ship source levels are deterministic constants for each class of ship and are independent of angle and time.	Same as DSBN, except that all ships in a lane have same deterministic constant speed and source level.
DSBN	Ship source level is a random variable depending on class, speed and length. The formula is $SL = K + 60 \log(\text{Speed}) + 20 \log(\text{Length})$, where K is a constant for each class, Speed and Length are uniform variables drawn independently for each ship. The levels are constant in time and independent of angle. Extension to include time or angle-dependent level is possible, but adds to computation load.	Ships travel on paths with Poisson arrival rule for input ship path density (like BTL). Route envelopes on lanes are defined, and within them ship properties (course, speed, level) are drawn from the same distributions, independently. Once initialized, ships sail (rectangularly) at constant course and speed. Lanes are initialized on circular arcs at edge of basin.
NABTAM	All surface ships have the same constant source level, derived from Ref. E-2, depending only on frequency.	Initial ship locations are a deterministic input. Initial courses and speeds can be user-specified or drawn from uniform and normal distribution, respectively. Once initialized, ships travel on tracks with dLAT/dt and dLON/dt constant. If a ship leaves the basin, it is not replaced.
SIAM I	Source intensity is a random variable for each ship, determined from distribution for ship class, and depending on frequency, and uniform or normal variables for speed and length. Default values are the same as for DSBN. Source intensity does not depend on time or transmission angle.	Ship locations, courses and speeds are initialized by class either deterministically (to match experimental data) or randomly (usually uniform). Once determined, the ships travel on great circle paths at constant speed and with constant source level. When a ship reaches the basin boundary it is reflected specularly (as in the WAGNER bounded noise process). As many as 250 ships are allowed.
SIAM II	Same as SIAM I	Initial ship courses and speeds are chosen from near-normal distribution, but then remain constant in time. Initial ship locations are uniform in subsectors. Ships are tracked in time on straight-line paths with reflections from subsector boundaries (see 2.9.3 for details).

Summary: BRUTE FORCE MODELS (II)

Model	Sound Transmission	Receiver
BEAMPL	Transmission loss is a deterministic input and is assumed to be independent of azimuth and time. There are no restrictions on the amount of detail permitted. The effects of vertical arrival structure, coherence, etc. are not included.	The receiver is a perfect horizontal array with fixed location and deterministic, time-independent response. In fact, the response in the horizontal is simply unity on the "main beam" and zero elsewhere. All energy is assumed to arrive as horizontal plane waves - perfectly coherent and undistorted.
DSBN	Same as BEAMPL, except that TL can be given as a function of azimuth and vertical arrival angle.	The model assumes an array at a fixed location with beam pattern. Subroutines generate canonical patterns for shaded and unshaded line arrays. All energy is assumed to arrive as plane waves, distributed in vertical angle, but perfectly coherent and undistorted. The model can account fully for the vertical multipath arrivals and their effect on array response for angles off broadside
NABTAM	Transmission loss is calculated within the model, using a geometric-acoustics approach without diffraction or coherence corrections, for a range-independent environment. The TL and vertical arrival structure are calculated for each of several receiver locations to all source ranges. The TL is deterministic and time-invariant.	Receiver locations, depths and beam-patterns are deterministic inputs. Internal routines can calculate beam patterns for standard line arrays. The three-dimensional response (including vertical multipath arrivals) is calculated as in DSBN Also there is a version of the model which performs "near-field" corrections, i.e., it calculates array responses for curved wavefronts from nearby sources.
SIAM I	A deterministic, time-independent TL as a function of range, azimuth, frequency and receiver depth is required for input. Up to 30 frequencies, 29 depths, and 10 azimuths are allowed. At each time sample an independent draw from a fluctuation distribution is added to the TL for each ship source. Also, there is a special "logarithmic" routine for interpolating TL in range and azimuth, and all geometry is spherical. The program can generate TL of form A+BlogR internally - as an option.	Same as BEAMPL except that multiple beam patterns can be treated in one program execution.
SIAM II	The model requires as input a table of TL versus range for as many as 16 azimuths, one frequency, and one receiver depth. A fluctuation component and A+BlogR routine are available, as in SIAM I.	Receiver location and depth are fixed. A single beam pattern, depending only on azimuthal arrival angle, is an input and defines the time-independent array response.

Summary: BRUTE FORCE MODELS (III)

Model	Basic Output	Output Analysis
BEAMPL	The basic model output is a sampled time series of beam noise for extended time periods (hours or days). Monte-Carlo simulation requires that a number of such replications be calculated. The model also produces a complete history of each ship.	The analysis package generates the statistics for the time series, including: (a) Time-averaged series (intensity average) for each replica, (b) Histograms, moments, percentiles for each replica, (c) Time-averaged autocorrelation function and its Fourier transform (dB's) for each replica, (d) Plots of (a), (b), (c). (e) A stationarity test is performed by finding moments and percentiles for subintervals of the time series. (f) Level crossing statistics - percentage of time noise is above a given value.
DSBN	Same as BEAMPL, except the series represents full array response - both from main beam and sidelobes. The model can also calculate the responses for several beampatterns at once (i.e., due to the same ship field), so that beam-to-beam correlation studies can be made. The model gives ship histories plus list of ships on main beam and on sidelobes.	Same as BEAMPL [(a) through (f)], plus: (g) Two-and three dimensional histograms (in time or beam), plus moments, cross-correlations, etc. (h) Comparison of intensity distribution with best fit chi-square (central and non-central), log-normal, etc. distributions. Kolmogorov test results and plots are displayed. (i) Ensemble density and statistics over all replications at one time period are found. (j) Extensive level-crossing results, including distribution of time intervals for which noise exceeds a level and waiting times to cross a threshold. (k) Complete history of beam-free and beam-occupied times.
NABTAM	Basic output consists of noise time series for each receiver location and beam pattern at one frequency. Monte-Carlo replications are not generated.	No analysis package is used at present, but a standard time-series statistics package could be applied.
SIAM I	Basic output is noise time series for each beam-pattern, frequency, and depth for extended time periods and multiple replications. Ship location histories are also available.	The analysis package provides the one-dimensional density function and moments for the ensemble of replications. Although autocorrelation functions can be found, their interpretation depends on the TL fluctuation model. Beamfree and occupied percentages and time histories are outputs.
SIAM II	Basic output consists of 32 realizations of beam-noise time series, for the single beam-pattern, frequency, and receiver location, and up to 128 time steps each.	An analysis package computes noise histograms, moments, and the median.

Summary: BRUTE FORCE MODELS (IV)

Model	Computation Costs	
BEAMPL	Approximately the same as for DSBN.	
DSBN	Costs depend on num of ships, number of beam patterns, replications, time period, amount of analysis, etc. Examples are (CDC 6400 computer): • 200 ships, 12 hours, 9 beam patterns, no analysis: $5/replication. • Analysis of 10 10-hour replications including (a), (b), (c), (d), (e), (f), (h), (i), (j), (k): $20. Core requirement for CDC 6400 is less than 40K words.	
NABTAM	Program is overlaid for minicomputer application, and core is 10K words (if not overlaid, 13K). Example of cost: one time step, large number of ships, five beam patterns: $0.75, on CDC 6400. Note, cost includes TL calculation.	
SIAM I	A typical run on the CDC 3800 requires 5-10 minutes computer time.	
SIAM II	Costs depend on ships, array response, subsectors, etc. For example, 25 ships, 32 realizations, 2 sectors, 128 time points per realization requires 10 minutes on the PDP 11/45 computer	

REFERENCES

A-1. Marshall, S. W., "Acoustic Performance of LAMBDA II in the CHURCH OPAL Experiment," NRL Memorandum Report 3418, Naval Research Laboratory, December (1976).

A-2. Papoulis, A., Probability, Random Variables, and Stochastic Processes, McGraw-Hill, New York (1965).

A-3. Parzen, E., Stochastic Processes, Holden-Day, San Francisco (1962).

A-4. Feller, W., An Introduction to Probability Theory and Its Applications, Vol. I, Wiley, New York (1957).

A-5. R. L. Jennette, Sander, E. L., Pitts, L. E., "The USI Array Noise Model, Version I, Vol. 1, Physics Documentation," USI-APL-R-8, April (1977).

A-6. R. L. Jennette, Sander, E. L., Pitts, L. E., "The USI Noise Model, Version I, Vol. 2, Computational Documentation," USI-APL-R-9, April (1977).

B-1. Goldman, J., "A Model of Broadband Ambient Noise Fluctuations Due to Shipping" (U), Bell Laboratories Report OSTP-31 JG, Contract N00039-74-C-0089 (1974).

B-2. Goldman, J., "A Shot Noise Model of the Random Fluctuations in Broadband Ambient Noise Caused by Shipping," Bell Laboratories Report OSTP-57 JG, Contract N00039-76-C-0122 (1977).

B-3. The impact of TL fluctuations on the BTL noise process has been recently studied in: Doles, J. H., III, "A Simple Model of Source Motion Induced Transmission Fluctuations with Application to Beam Noise Fluctuations" (U), Bell Laboratories Report, Contract N00039-76-C-0122, November (1976).

C-1. Mahler, J. I., Sullivan, F. J. M., and Moll, M., "Statistical Methodology for the Estimation of Noise Due to Shipping in Small Sectors and Narrow Bands," BBN Tech Memo W273, Bolt Beranek and Newman, Inc., June (1975).

C-2. Moll, M., Zeskind, R. M., Sullivan F. J. M., "Statistical Measures of Ambient Noise: Algorithms, Program, and Predictions," BBN Report 3390, Bolt Beranek and Newman, Inc., June (1977).

C-3. Heine, J. and Gray, L., "Merchant Ship Radiated Noise Model," BBN Report 3020, Bolt Beranek and Newman, Inc., June (1975).

D-1. McCabe, B. J., "Ambient Noise Effects in the Modeling of Detections by a Field of Sensors," D. H. Wagner, Assoc. Report to ONR 431, Contract N00014-76-C-0637, November (1976).

D-2. Marlow, N. A., "A Normal Limit Theorem for Power Sums of Independent Random Variables," The Bell System Tech. J., 2081-2089, November (1967).

D-3. Doob, J. L., "The Brownian Movement and Stochastic Equations," Annals Math. 43, 351-369 (1942). Reprinted in Wax, N. (Ed.), Noise and Stochastic Processes, Dover, New York, (1954).

E-1. Cornyn, J. J., "A Narrow Beam Towed Array Model (NABTAM version 1.0)," NORDA Publication (in press) (1977).

E-2. Ross, D. and Alvarez, F. F., "Radiated Underwater Noise of Surface Ships," U.S. Navy J. Underwater Acoustics 14 (1964).

E-3. Talham, Robert J., "Ambient-Sea-Noise-Model," J. Acoust. Soc. Am. 36, 1541-1544 (1964).

F-1. Cavanagh, R. C., "Acoustic Fluctuation Modeling and System Performance Estimation," Final Report to ONR 431, Science Applications, Inc. (In Revision) (1977).

F-2. Conover, W. J., Practical Nonparametric Statistics, Wiley, New York (1971).

H-1. Marshall, S. W. and Cornyn, J. J., "Ambient-Noise Prediction, Volume 1 - Model of Low-Frequency Ambient Sea Noise," NRL Report 7755, Naval Research Laboratory, June 21, 1974.

H-2. Marshall, S. W. and Cornyn, J. J., "Ambient-Noise Prediction, Vol 2 - Model Evaluation with IOMEDEX Data," NRL Report 7756, Naval Research Laboratory, July 1, 1974.

I-1. Marshall, S. W., "Acoustic Signal-to-Noise and Azimuthal Noise Directionality in the Mediterranean Sea Using LAMBDA II," NRL Memorandum Report 3050, April 15, 1975.

I-2. Naval Ocean Research and Development Activity, "A Prediction of the Azimuthally Dependent Low-Frequency Ambient Noise at CHURCH STROKE TWO Site A," Acoustic Modeling Branch (Draft), August 1977.

DISTRIBUTION LIST

Assistant Secretary of the Navy
(RE&S)
Washington, D.C. 20301
Attn: G. A. Cann 1

Chief of Naval Operations
Department of the Navy
Washington, D.C. 20350
Attn: OP-095 1
OP-951 1
OP-955 1
OP-95E 1
OP-096 1

Chief of Naval Development
Headquarters, Naval Material
Command
Washington, D.C. 20360
Attn: MAT-035 1

Commander
Oceanographic Systems, Atlantic
Box 100
Norfolk, VA 23511 2

Commander
Oceanographic Systems, Pacific
Box 1390
Pearl Harbor, HI 96860
Attn: CDR R. C. Leavitt 1

Chief of Naval Research 1
Department of the Navy
Arlington, VA 22217
Attn: Dr. J. B. Hersey 1
Code 431 1

Office of Naval Research
Branch Office
1030 East Green Street
Pasadena, CA 91106 1

Commanding Officer 1
Naval Research Laboratory
Washington, D.C. 20375
Attn: Code 8100 1
Code 8160 1
Code 2627 1

Oceanographer of the Navy
Hoffman Building II
200 Stovall Street
Alexandria, VA 22332
Attn: CDR E. T. Young 1

Commander
Naval Air Systems Command
Department of the Navy
Washington, D.C. 20360
Attn: Code PMA-264 1

Commander
Naval Electronic Systems
Command
Department of the Navy
Washington, D.C. 20360
Attn: PME-124, 124/30, /40, /60 4
ELEX-320 1
ELEX-035 1

Commander 1
Naval Sea Systems Command
Department of the Navy
Washington, D.C. 20362
Attn: SEA-06H1 1

Strategic Systems Project
Office
Department of the Navy
Washington, D.C. 20360
Attn: PM-1 1

Anti-Submarine Warfare
Systems Project Office
Department of the Navy
Washington, D.C. 20360
Attn: PM-4 2

Commanding Officer and Director
Defense Documentation Center
Defense Services Administration
Cameron Station, Building 5
5010 Duke Street
Alexandria, VA 22314 2

Commanding Officer 1
Fleet Numerical Weather
Central
Monterey, CA 93940

Commander 1
Naval Ocean Systems Center
San Diego, CA 92132
Attn: M. R. Akers 2
R. A. Wagstaff 1
E. B. Tunstall 1
R. R. Gardner 1

DISTRIBUTION LIST (CONT'D)

Commander
Naval Surface Weapons Center
White Oak Laboratory
Silver Spring, MD 20910 — 1

Commander
Naval Underwater Systems Center
New London Laboratory
New London, CT 06320 — 1
Attn: R. L. Martin — 4

Commander
David M. Taylor Naval Ship Research and Development Center
Bethesda, MD 20034 — 1

Commander
Naval Air Development Center
Warminster, PA 18974 — 2

Commander
Naval Oceanographic Office
Department of the Navy
Washington, D.C. 20373 — 1
Attn: J. L. Kerling — 1

Commanding Officer
Naval Intelligence Support Center
4301 Suitland Rd.
Washington, D.C. 20390 — 1

Director for Naval Matters
Center for Naval Analysis
Arlington, VA 22209 — 1
Attn: C. E. Woods — 1

Commanding Officer
Naval Ocean Research and Development Activity
NSTL Station, MS 39529 — 1
Attn: Code 110 — 1
Code 200 — 1
Code 300 — 1
Code 320 — 1
Code 340 — 1
Code 400 — 1
Code 500 — 1
Code 600 — 3

NORDA Liaison Office
Office of Naval Research
Arlington, VA 22217
Attn: K. W. Lackie — 2

Defense Advanced Research Projects Agency
1400 Wilson Boulevard
Arlington, VA 22209 — 1

ARPA Research Center
Unit 1, Bldg. 301A
NAS Moffett Field, CA 94035
Attn: E. L. Smith — 1

Superintendent
Naval Postgraduate School
Monterey, CA 93940
Attn: Library — 1

Analysis & Technology, Inc.
Rt 2
North Stonington, CT 06359
Attn: S. Elam — 1

Applied Physics Laboratory
Johns Hopkins University
Johns Hopkins Road
Laurel, MD 20810
Attn: G. L. Smith — 1

Applied Physics Laboratory
University of Washington
1013 NE Fortieth Street
Seattle, WA 98195 — 1

Applied Research Laboratories
University of Texas
P. O. Box 8029
Austin, TX 78712
Attn: G. E. Ellis — 1
L. D. Hampton — 1

Arthur D. Little, Inc.
15 Acorn Park
Cambridge, MA 02140
Attn: W. G. Sykes — 1

Bell Telephone Laboratories
1 Whippany Road
Whippany, N.J. 07981
Attn: J. Goldman — 1

DISTRIBUTION LIST (CONT'D)

B-K Dynamics, Inc.
15825 Shady Grove Road
Rockville, MD 20850
Attn: P. G. Bernard 1

Bolt Beranek and Newman, Inc.
1701 N. Fort Myer Drive
Suite 1001
Arlington, VA 22209
Attn: M. Moll 1

Bolt Beranek and Newman, Inc.
50 Moulton Street
Cambridge, Massachusetts 02138
Attn: J. Heine 1

Bunker-Ramo
31717 La Tienda Drive
Westlake Village, CA 91361
Attn: R. K. Fullerton 1

Daniel Analytical Services Corp. 1
16821 Buccaneer Lane
Houston, TX 77058

Daniel H. Wagner Associates
Station Square One
Paoli, PA 19301
Attn: B. J. McCabe 1

Daubin Systems Corporation 1
104 Crandon Blvd.
Suite 315
Key Biscayne, FL 33149

General Electric Corp.
Farrell Road Plant
Syracuse, NY 13201
Attn: K. D. Greenhalgh 1

General Electric Corp.
Reentry Environmental Sys. Div.
3198 Chestnut St.
Philadelphia, PA 19101
Attn: O. Klima 1

Lockheed Missiles and Space Company, Inc.
P. O. Box 504
Sunnyvale, CA 94088
Attn: R. C. Parsons 1

University of California, San Diego
Marine Physical Laboratory of the Scripps Inst. of Oceanography
San Diego, CA 92132
Attn: V. C. Anderson 1

Chairman
Department of Ocean Engineering
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139
Attn: Prof. I. Dyer 1

Operations Research, Inc.
1400 Spring Street
Silver Spring, MD 20910
Attn: J.I. Bowen 1
E.J. Moses 1

Palisades Geophysical Institute, Inc. 1
131 Erie Street
P. O. Box 396
Blauvelt, NY 10913

Pennsylvania State University
Applied Research Laboratory
P. O. Box 30
State College, PA 16801
Attn: D. C. Stickler 1

Planning Systems, Inc.
7900 Westpark Drive
McLean, VA 22101
Attn: L. P. Solomon 1

Raytheon Company
Submarine Signal Division
P. O. Box 360
Portsmouth, RI 02871
Attn: B. A. Becken 1

Summit Research Corp. 1
1 West Deer Park Drive
Gaithersburg, MD 20760

Sutron Corporation
1925 N. Lynn Street
Suite 700
Arlington, VA 22209
Attn: C. H. Dabney 1

DISTRIBUTION LIST (CONT'D)

Systems Integrated
9961 Cowan Heights Drive
Santa Ana, CA 92705
Attn: L. Pomatto 1

Tetra Tech, Inc.
1911 N. Fort Myer Drive
Arlington, VA 22209
Attn: W. E. Sims 1

Texas Instruments, Inc.
P. O. Box 6015
Dallas, TX 75222
Attn: A. Kirst, Jr. 1

Tracor, Inc.
6500 Tracor Lane
Austin, TX 78721
Attn: A. F. Wittenborn 1

Tracor, Inc.
1601 Research Blvd.
Rockville, MD 20850
Attn: J. T. Gottwald 1

TRW Systems Group
7600 Colshire Drive
McLean, VA 22101
Attn: R. T. Brown 1
I. B. Gereben 1

Undersea Research Corporation
7777 Leesburg Pike, Suite 306
Falls Church, VA 22043
Attn: V. F. Anderson 1

Underwater Systems, Inc.
World Building
8121 Georgia Avenue
Silver Spring, MD 20910
Attn: M. S. Weinstein 1
R. L. Jennette 1

Western Electric Company 1
2400 Reynolds Road
Winston Salem, NC 27106

Westinghouse Electric Co. 1
P. O. Box 1488
Mail Stop 9R40
Annapolis, MD 21404

Woods Hole Oceanographic
Institution
Woods Hole, MA 02543
Attn: E. E. Hays 1

Xonics, Inc.
6837 Hayvenhurst Avenue
Van Nuys, CA 91406
Attn: S. Kulek 1

DEPARTMENT OF THE NAVY
OFFICE OF NAVAL RESEARCH
875 NORTH RANDOLPH STREET
SUITE 1425
ARLINGTON VA 22203-1995

IN REPLY REFER TO:

5510/1
Ser 321OA/011/06
31 Jan 06

MEMORANDUM FOR DISTRIBUTION LIST

Subj: DECLASSIFICATION OF LONG RANGE ACOUSTIC PROPAGATION PROJECT (LRAPP) DOCUMENTS

Ref: (a) SECNAVINST 5510.36

Encl: (1) List of DECLASSIFIED LRAPP Documents

1. In accordance with reference (a), a declassification review has been conducted on a number of classified LRAPP documents.

2. The LRAPP documents listed in enclosure (1) have been downgraded to UNCLASSIFIED and have been approved for public release. These documents should be remarked as follows:

   Classification changed to UNCLASSIFIED by authority of the Chief of Naval Operations (N772) letter N772A/6U875630, 20 January 2006.

   DISTRIBUTION STATEMENT A: Approved for Public Release; Distribution is unlimited.

3. Questions may be directed to the undersigned on (703) 696-4619, DSN 426-4619.

BRIAN LINK
By direction

Subj: DECLASSIFICATION OF LONG RANGE ACOUSTIC PROPAGATION PROJECT (LRAPP) DOCUMENTS

DISTRIBUTION LIST:

NAVOCEANO (Code N121LC – Jaime Ratliff)
NRL Washington (Code 5596.3 – Mary Templeman)
PEO LMW Det San Diego (PMS 181)
DTIC-OCQ (Larry Downing)
ARL, U of Texas
Blue Sea Corporation (Dr.Roy Gaul)
ONR 32B (CAPT Paul Stewart)
ONR 321OA (Dr. Ellen Livingston)
APL, U of Washington
APL, Johns Hopkins University
ARL, Penn State University
MPL of Scripps Institution of Oceanography
WHOI
NAVSEA
NAVAIR
NUWC
SAIC

Declassified LRAPP Documents

Report Number	Personal Author	Title	Publication Source (Originator)	Pub. Date	Current Availability	Class.
DASC 012-C-77	Unavailable	LRAPP PACIFIC DYNAMIC ARCHIVE (U) SEPTEMBER 1976	Daniel Analytical Services Corporation	770201	NS; ND	U
SAI-78-527-WA	Spofford, C. W.	NELANT DATA ASSESSMENT APPENDIX III-MODELING REPORT	Science Applications, Inc.	770225	~~ND~~ ADA 047 680	U
PSI TR 036049	Barnes, A. E., et al.	OCEAN ROUTE ENVELOPES	Planning Systems Inc.	770419	ND	U
Unavailable	Unavailable	TAP II BEAMFORMING SYSTEM SOFTWARE FINAL REPORT	Bunker-Ramo Corp. Electronic Systems Division	770501	ADC011789	U
S01037C8	Unavailable	TAP 2 PROCESSING SYSTEM FINAL REPORT HARDWARE DOCUMENTATION (U)	Bunker-Ramo Corp. Electronic Systems Division	770501	ADC011790; NS; ND	U
Unavailable	Weinberg, H.	GENERIC FACT	Naval Underwater Systems Center	770601	ADB019907	U
Unavailable	Unavailable	TASSRAP II OB SYSTEM TEST	Analysis and Technology, Inc.	770614	ADA955352	U
Unavailable	Unavailable	LRAPP TECHNICAL SUPPORT	Texas Instruments, Inc.	770624	ND	U
Unavailable	Bessette, R. J., et al.	TASSRAP INPUT MODULE	Analysis and Technology, Inc.	770729	ADA955340	U
Unavailable	Unavailable	TAP-II PHASE II FINAL REPORT	Bunker-Ramo Corp. Electronic Systems Division	770901	ADC011791	U
Unavailable	Unavailable	LONG RANGE ACOUSTIC PROPAGATION PROJECT (LRAPP)	Xonics, Inc.	770930	ADA076269	U
SAI78696WA	Unavailable ADA 055 728	REVIEW OF MODELS OF BEAM-NOISE STATISTICS (U)	Science Applications Inc.	771101	NS; ND	U
TRACORT77RV109C	Unavailable	FINAL REPORT FOR CONTRACT N00014-76-C-0066 (U)	Tracor Sciences and Systems	771130	ADC012607; NS; ND	U
Unavailable	Unavailable	LONG RANGE ACOUSTIC PROPAGATION PROJECT (LRAPP)	Xonics, Inc.	771231	ADB041703	U
Unavailable	Homer, C. I.	SUS SOURCE LEVEL ERROR ANALYSIS ADA 055 660	Underwater Systems, Inc.	780120	ND	U
Unavailable	Fitzgerald, R. M.	LOW-FREQUENCY LIMITATION OF FACT	Naval Research Laboratory	780131	ADA054371	U
Unavailable	Unavailable	MIDWATER ACOUSTIC MEASUREMENT SYSTEM - PAR AND ACODAC	Texas Instruments, Inc.	780228	ADB039924	U
ORI TR 1245	Moses, E. J.	OPTIONS, REQUIREMENTS, AND RECOMMENDATIONS FOR AN LRAPP ACOUSTIC ARRAY PERFORMANCE MODEL	ORI, Inc.	780331	ND	U
Unavailable	Hosmer, R. F., et al.	COMBINED ACOUSTIC PROPAGATION IN EASTPAC REGION (EXERCISE CAPER): INITIAL ACOUSTIC ANALYSIS	Naval Ocean Systems Center	780601	ADB032496	U
LRAPPRC78023	Watrous, B. A.	LRAPP EXERCISE ENVIRONMENTAL DATA INVENTORY, JUNE 1978 (U)	Naval Ocean R&D Activity	780601	NS; ND	U
TR052085	Solomon, L. P., et al.	HISTORICAL TEMPORAL SHIPPING (U)	Planning Systems Inc.	780628	NS; ND	U